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GENERAL ELECTRIC UNATTENDED POWER SYSTEM STUDY ADDENDUM

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The General Electric 2 KW(e) Unattended Power System Study was conducted in 1976-77 to analyze the cost and risk associated with the development of alternative power systems capable of supplying 2 KW(e) in an unattended mode in an Arctic environment. The study concluded that a diesel power system was the most attractive alternative for an unattended radar (UAR) station prime power generation and distribution system.

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20. ABSTRACT (concluded)

This paper extends the General Electric Study by examining three of the candidate systems in more detail and updating cost estimates based on a change in the power requirements to 5 KW(e). The three systems chosen for further examination are diesel power systems, fuel cell power plants, and an organic Rankine cycle turbogenerator, the Ormat Energy Converter.

STOP

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NOTICE

The SEEK FROST Program was deferred for Fiscal Year 1980 by Congress. Funding and active USAF program activities terminated 30 September 1979.

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GENERAL OVERVIEW

1.1 INTRODUCTION

The SEEK FROST Program is intended to provide an Enhanced Distant Early Warning (EDEW) system by employing 13 Minimally Attended Radar (MAR) Stations, and 57 Unattended Radar (UAR) Stations. Each UAR Station will include an unattended, short range radar to fulfill the low altitude gapfilling role, the necessary facilities to support and house the equipment, and emergency shelter for maintenance personnel.

A key element in the development of an unattended radar station design is the need for a highly reliable prime power source capable of operating in an unattended mode in the extreme conditions of an Arctic environment. The choice of a power system will impact the UAR station reliability, the UAR station acquisition cost, and the maintenance cost required to keep the UAR station operational.

1.2 PURPOSE

As an addendum to the General Electric Unattended Power System Study(1), this report is intended to examine the following areas: (1) for selected prime power systems considered for further study, the GE Study is updated in areas which are significantly influenced by a change in the continuous power requirement from 2 KW(e) to 5 KW(e); (2) the performance of selected systems is examined in more detail based on operational experience in an unattended mode; (3) certain areas of cost data in the GE Study concerning the acquisition and ownership of selected systems are updated based on proposed changes in power system configurations and recent vendor contacts.

This report will concentrate primarily on three systems which are considered by the author to be the most attractive for the SEEK FROST Program in terms of development risk, cost-effectiveness, reliability, and maintainability. The systems selected are: (1) Lister diesel-driven generator sets, (2) the Ormat Energy Converter (an organic Rankine cycle turbogenerator), and (3) fuel cell power plants.

It is the author's intent to provide enough information concerning the operation of these systems to enable this report to be a stand-alone document. Detail will be provided in areas which were not covered sufficiently in the GE Study or in areas that are unique to this report. If the reader desires more detailed technical

information concerning system definition and conceptual design of these (or other) power systems, the aforementioned GE Study should be referenced. It should be noted that the amount of information presented in this report for each of the systems considered was governed by the data made available to the author, and by the detail provided in the GE Study concerning these systems.

In addition to the three systems chosen for detailed analysis in this report, other alternatives and issues have been considered at various levels of detail. Where appropriate, these issues will be discussed and rationale for the conclusions which were reached will be given.

1.3 REQUIREMENTS

The requirements for prime power generation and distribution for unattended radar stations are given in another document. Currently envisioned is a prime power source capable of unattended operation in an Arctic environment which provides 5 KW(e) of prime power for full time operation of the UAR station facilities, communications, and radar equipment. In addition, the system must be capable of providing 10 KW(e) of prime power during those periods when maintenance personnel are on-site (this amount of time is assumed to be no more than 15 days per year and no more than 3 days per visit).

With the exception of broadly defined requirements for an emergency back-up supply to the primary power generator and load-switching capability upon prime power failure, the system specification contains no other operational requirements, such as reliability, maintainability, lifetime, etc. The GE Study has identified several operational requirements for the potential power systems, along with constraints on the physical characteristics of the system. For the purpose of this report, the systems of interest will be required to: (1) meet the terms of the SEEK FROST System Specification, (2) be potentially capable of operating in an unattended mode in an Arctic environment, and (3) be helicopter transportable. The remaining operational characteristics will be used as criteria by which the candidate systems are to be evaluated.

1.4 EVALUATION OF THE CANDIDATE SYSTEMS

Several approaches to evaluating the candidate power systems are possible. The approach chosen for the purposes of this report is to insure initially that each of the systems meets the three

requirements given above. Each of the systems is then to be evaluated in terms of reliability, maintainability, operational experience (if applicable), acquisition and ownership costs, and any other factors which may be peculiar to the system which are considered to have an effect (favorable or adverse) on its desirability as an unattended power source for the SEEK FROST Program. Thus, the operational characteristics of a system will not be matched against a set of requirements, which must be satisfied before the system is considered a potential choice as a prime power source. Rather, the system's operational characterisitcs will be identified and judged relative to those of the other systems to help indicate where the strengths and weaknesses of each candidate system lie.

This approach has the advantage of allowing systems to be evaluated in terms of criteria which may not lend themselves to a cost quantification. This will permit consideration of development risk, demonstrated Arctic performance, ease of handling, and other criteria which may not directly effect the life cycle cost of a system, but which nonetheless deserve consideration in evaluating the system. Hence, this report is attempting to do more than merely identify a 'least cost' system; rather, it hopes to identify the system which will provide the best performance relative to its cost.

1.5 LIFE CYCLE COST MODEL

As previously mentioned, one of the purposes of this report is to provide updated cost data concerning the acquisition and ownership of the power systems of interest. Portions of the cost data presented in the GE Study concerning the systems of interest are still considered to be the best estimates available. (These elements will be identified when cost data is given.) However, due to such factors as changes in power system configuration and technology advances since the publication of the GE Study, portions of the cost data in the report need to be updated.

In order to give the costs associated with a system as much visibility as is possible with the data available, the following model has been chosen to represent the life cycle (including 20-year Operations and Support) costs associated with each of the candidate systems:

$$LCC = DEV + PROC + INST + [MAINT + FUEL + FUEL\ TRANSP] \times PIUP$$

where

DEV = the cost to develop the power system or any cost incurred as a result of applying an existing technology to meet the SEEK FROST requirements (not included in per-site LCC)

PROC = the cost of acquiring the power system module, including the shelter and environmental protection unit, and fuel storage tanks

INST = the cost of site preparation, shipping of the system to the site, installation and check-out of the system on the prepared site foundation

MAINT = annual cost (labor and parts) of maintaining the operational status of the power system

FUEL = annual cost of power system's fuel excluding helicopter shuttle from resupply vessels to the UAR station

FUEL TRANSP = annual cost associated with transporting fuel from resupply ships to the UAR stations by helicopter airlift

PIUP = power system operating lifetime (20 years)

Due to the uncertainty which presently exists with respect to the number of UAR sites that will be required (the baseline being 57 UAR sites), the approach to life cycle costing is to calculate the cost of acquisition and ownership of each candidate system for a single UAR site. Given a value for the number of sites, it is then possible to arrive at an estimate of prime power cost for all of the SEEK FROST UAR stations by multiplication. For this reason, the development cost associated with a system is not included in the life cycle cost of prime power generation for a single site. However, development costs are to be considered as part of the life cycle cost when using this criterion as a means for comparison of the candidate systems.

Detailed explanations of what is included in each of the above cost elements will be given when the cost data associated with each of the candidate systems is presented. However, the two cost elements for FUEL and FUEL TRANSP will be computed in the same manner for all systems. The methodology employed in these calculations is described in the following sections.

1.5.1 Calculation of Annual Fuel Cost

The calculation of the cost of fuel for a particular power system is straightforward. First, the consumption rate of the system is determined, and then it is multiplied by the unit cost of the fuel under consideration, giving the annual fuel cost.

The unit cost of a given fuel will be composed of two parts -- the purchase price of the fuel in CONUS and the cost of sealift from CONUS to the UARS. The purchase price will depend upon the fuel type, but the shipping costs will be assumed constant for all types of fuel and will be determined from information supplied by the DEW Systems Office.

The most recent jet fuel (JP-4) buy was quoted at an average cost of $.78/gallon delivered to the current DEW sites. Contacts with personnel in the DEW Systems Office indicated that this cost represented $.50/gallon for the fuel itself plus $.28/gallon for the sealift to the sites. At a weight of 6.5 pounds/gallon, this represents a cost of $.043/pound for the sealift transport. This value will be used in computing the unit cost of other fuels being considered.

1.5.2 Calculation of Cost of Helicopter Shuttle of Fuel

The cost calculation described in Section 1.5.1 gives the cost of fuel before consideration of the transfer of the fuel to the site storage facility from the resupply vessel. This section describes the helicopter shuttle operation which will transport the fuel from the resupply vessel to the UAR site fuel storage tank(s). The approach is based on a procedure proposed in a report concerning helicopter support for the SEEK FROST Program. A discussion on estimating the cost of this operation is then given.

The refueling of the UAR sites will take place once per year during the summer. Helicopters based at the main stations will be dispatched with the necessary personnel to the UAR site and make connections with the resupply vessels transporting the fuel. The fuel will be loaded in 5000 pound capacity metal drums which will be sling-lifted from the vessel to the UAR site storage tank. This process is repeated until the tank is filled, at which time the vessel and helicopter move on to the next site.

The personnel required for the operation include the helicopter crew, a hook-up man at the ship and site, and two personnel to transfer the fuel to the storage tank. This mode of operation is considered routine in field operations and is felt to present no difficulties as a logistics task.

The main area of concern for estimating the cost of this operation is the amount of flying time for the helicopter, as this will drive the cost of the shuttle. Average time factors are given in the previously referenced report as follows: five minutes to hook-up tanks at the vessel and at the site and five minutes flying time between the pickup and discharge points. Therefore, to estimate the cost of the helicopter shuttle, the only inputs required will be the fuel requirement of the site, the cargo sling capacity of the helicopter (these two inputs will allow determination of the number of trips required from the resupply vessel to the site), the cost per flight hour for the helicopter, and the cost of the support personnel. These inputs will be examined in detail for each of the candidate systems when presenting life cycle costs for the systems.

SECTION 2

ANALYSIS OF CANDIDATE SYSTEMS

2.1 ORMAT ENERGY CONVERTOR (OEC)

The Ormat Energy Convertor is a prime power system manufactured in Israel by Ormat Turbines Ltd. and marketed by Ormat Systems, Inc. of Hopkinton, Massachusetts.

2.1.1 Description

The OEC is a hermetically sealed organic Rankine cycle turbogenerator which is delivered fully integrated, tested, and certified. The system consists of a combustion system, vapor generator, turboalternator, air-cooled condenser, rectifier, alarms, and controls all housed in a single shelter. Figure 1 shows a typical OEC unit as it appears ready for deployment.

The OEC units are capable of supplying from 200 to 6000 watts of filtered DC power on a continuous basis for periods up to 20 years. The systems are designed for unattended operation for extended periods of time with minimal maintenance requirements. This performance is possible due to the system containing only one moving part --a smoothly rotating shaft on which the turbine wheel, alternator rotor, and return feed pump are mounted. This shaft is supported by working fluid film bearings, eliminating any metal-to-metal contact.

2.1.2 Operation

The organic Rankine cycle is basically a steam turbine cycle with an organic working fluid replacing the steam. This allows the process to extract work more efficiently from low-temperature heat sources.

Figure 2 shows a cut away view of the OEC unit. The process by which electrical energy is produced is a closed cycle which begins with the burner heating an organic fluid in the vapor generator. The vapor expands through a turbine wheel to produce shaft power to drive the alternator. The turbo-alternator produces three phase AC power which is rectified and filtered.

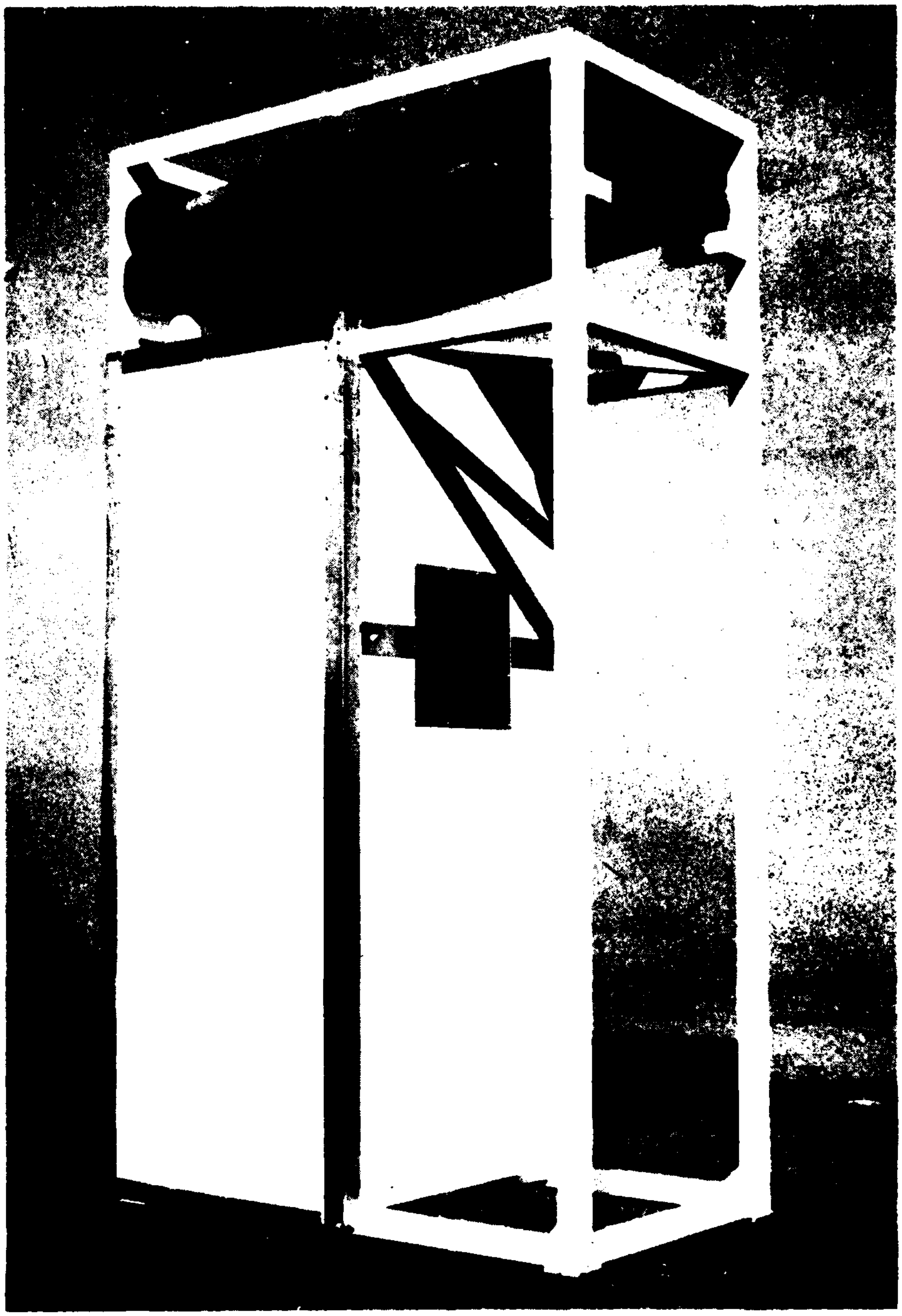


Figure 1. Ormat Energy Converter

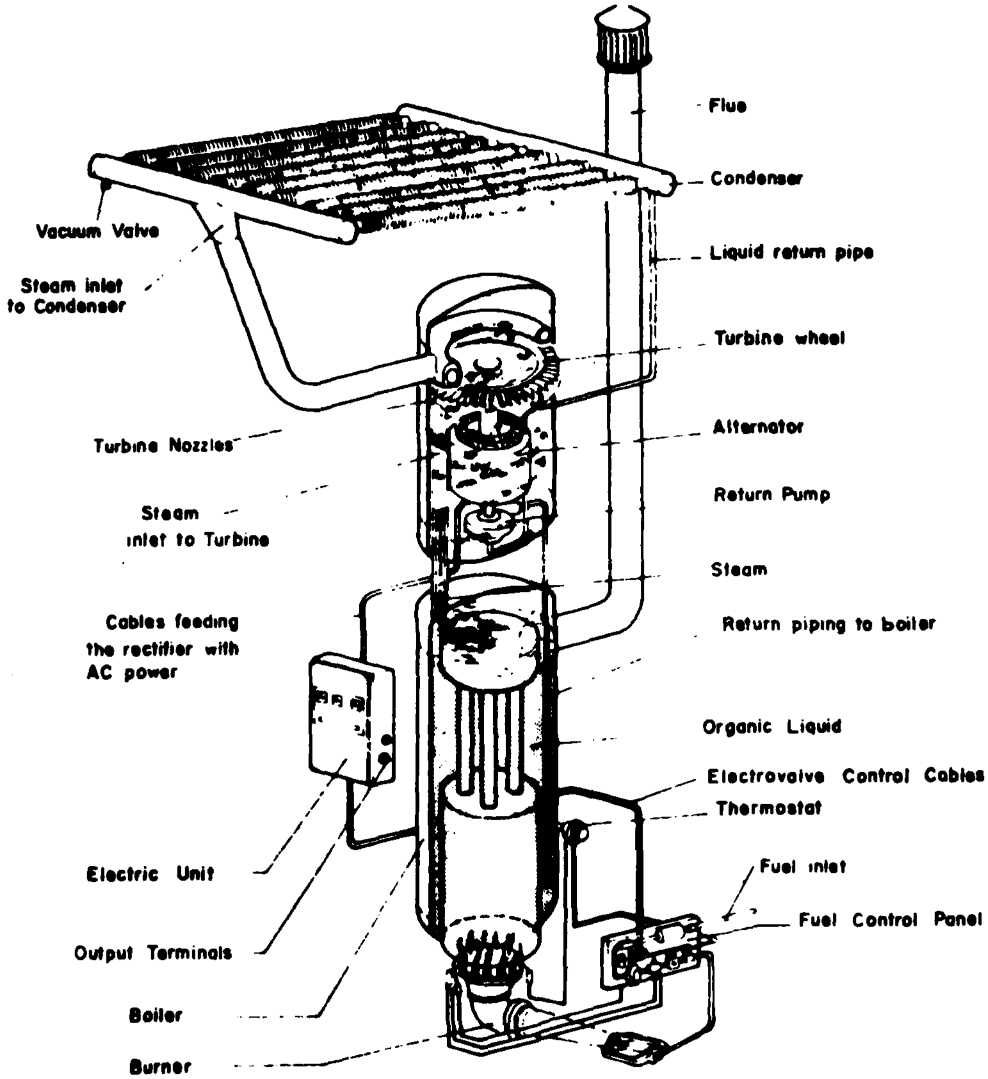


Figure 2. Ormat Energy Converter

Working Principle

The vapor passes into a condenser, is cooled, and condenses back into a liquid state. It is then pumped back into the vapor generator for reheating, completing the cycle. It is during the return to the vapor generator that the fluid acts as a coolant for the alternator and lubricant for the bearings supporting the turbo-alternator shaft.

The cycle will continue as long as heat is applied to the vapor generator. Due to the hermetically sealed, closed cycle design, there is no loss of organic working fluid in this process.

The regulation of the voltage output is ultimately controlled by the burner control system. This is easily understood by considering the following: the alternator rotor is mounted on the same shaft as the turbine wheel and its output voltage therefore depends on the rotational speed of the turbine. This speed is determined by the quantity of vapor passing through the turbine, which is a function of the amount of heat supplied from the burner to the vapor generator. This amount of heat is under the control of the burner control system.

The system is capable of responding to varying load conditions through the use of voltage sensors which cause changes in the firing rate of the burner. For large reductions in load in a single step, it may be necessary for the system to substitute a series of dummy loads for the removed load in order to limit the voltage rise within acceptable levels. As the output voltage drops, the dummy loads are shed and the system returns to steady state condition.

A crucial element in the operation of the OEC is the performance of the working fluid, as this will directly effect the cycle's efficiency. The physical features which are desired of a working fluid, due to their impact on its performance in the Rankine cycle, include: (1) high molecular weight, (2) a boiling point in the range of 100-200°C, (3) chemical stability against decomposition or loss resulting from a continuous heat-cool cycle, (4) non-corrosiveness to conventional constructional materials under prolonged heating.

The exact composition of the working fluid used in the OEC is considered proprietary information by the people at Ormat Systems. The fluid has a monochlorobenzene base with various additives, the amount and type of the additives varying depending on the environment in which the units are deployed. For Arctic applications, the additives are chosen so that the OEC is capable of continuous operation in ambient temperatures of -76°F to 100°F. Other additives allow operation in arid environments up to 122°F.

2.1.3 Fuel

One feature of the OEC operating concept is its fuel versatility; that is, the units are able to operate on a variety of fuels and heat sources. Since the fluid cycle is closed and external to the burner system, any source of heat applied to the vapor generator will allow the system to operate. Thus, no changes are required in the vapor generator, turbo-alternator, condenser, frame, and shelter if a change in fuel is desired. Only minor, inexpensive changes in the fuel panel, portions of the electrical control panel, and type of burner are required to convert from one type of fuel to another.

The choice of a fuel is largely dependent on: (1) the operating environment of the unit, (2) the availability of various types of fuel, and (3) the cost of the fuels which are available. For OEC units deployed in remote locations (such as microwave relay stations) which will have extended periods of time (one year) between maintenance visits, liquid petroleum gas (LPG) is desirable because of its purity. Other fuels which do not burn as cleanly, such as jet and diesel fuel, are popular because of their availability. If these fuels are to be used, maintenance visits will be required approximately every six months for cleaning of the burner.

Some applications offer unique fueling arrangements. For the OEC units deployed at remote locations along the Australian Natural Gas Pipeline, fuel is supplied directly from the gas pipeline, thereby eliminating the cost of refueling visits. For units deployed near piped petroleum crude oil, diesel fuel distilled from the crude may be used as a fuel source. Some units have been designed with fuel change-over systems that automatically switch from natural gas to LPG should one or the other fuel source be interrupted.

This versatility affords an area of study for cost reduction and trade-offs when choosing a fuel source. In addition, the decision reached is not necessarily final, as changing conditions (such as the cost of a given fuel) may warrant a change in fuel at some later date. This conversion can be easily, and economically, implemented. This area will be examined in more detail later.

In addition to these conventional fuel sources, OEC units have been designed to run using less common heat sources, among them solar energy and nuclear isotope fuels.

2.1.4 Configuration

To meet the prime power requirements of 5 KW during unattended operation and 10 KW during periods when maintenance personnel are on-site, Ormat representatives recommend the Ormat Hybrid Turbo-generator System which is currently available for procurement. The system is comprised of two OECs which operate in a load-sharing mode to achieve lower rates of fuel consumption and very high levels of reliability. The following paragraphs describe the system's mode of operation in detail.

The two OECs operate simultaneously, each supplying one-half (2.5 KW) of the required load. As fuel consumption of the OEC is basically linear with respect to load, the primary unit consumes 50% of the fuel required to supply the entire station load by itself.

The secondary unit supplies the balance of the power (2.5 KW), but through efficient utilization of waste heat from the primary unit (normally rejected to the atmosphere from the condenser), this unit requires only an additional 10% of the fuel needed to supply the entire 5 KW station load on its own. To further enhance the efficiency of this mode of operation, the secondary unit uses a working fluid which has a lower boiling point and is therefore easier to vaporize.

Using this configuration, the hybrid system will consume only 60% of the fuel of either unit operating alone and supplying the entire 5 KW station load. In addition, upon failure of either unit, the other unit automatically assumes the full 5 KW load through the operation of the monitor and control system. This provides high levels of reliability as there is total redundancy in the system with each unit on hot standby should the other fail. This operating mode therefore eliminates any possibility of start-up failures that may be inherent with other types of systems.

The electrical energy efficiency of the hybrid system is approximately 11% in the load-sharing mode. The efficiency drops to 7% should one unit be required to assume the full 5 KW load on its own. (For a liquid-fueled OEC system, a small blower is included in the combustion system to force air to the flame resulting in cleaner combustion. This requires 100 watts of power and has the effect of reducing the overall efficiency of the system, on the order of a few tenths of a percent. This reduction is considered negligible for the purposes of this report.)

2.1.5 Reliability

OEC units have been deployed in countries throughout the world in all types of terrain and climate (Arctic, tropical, desert) since the early 1970's. The output of these units ranges from 200 to 3000 watts for applications including microwave links for communications systems, telecommunications, T.V. transponders, airport equipment, and power for remote pipeline stations to operate meters, sensors, communications equipment, etc. (OEC units with output up to 6000 watts are currently available which utilize the same operating concept as the smaller units.)

Through the end of 1976, more than ten million operating hours had been recorded. Based on this field experience, Ormat Systems has applied statistical techniques to the data to derive estimates of MTBF. The techniques used were chosen to give the concept of estimated MTBF a more intuitive meaning for the potential user. Essentially, a confidence level (probability) is selected, within which one can assert that the true MTBF of the system will not fall below some specified value.

The field data collected from OEC units currently deployed was used in the estimation of MTBF and led to the result that the probability is .95 that the true MTBF of the turbo-alternator unit (which contains the only moving part in the system) will fall no lower than 300,000 hours. For the entire OEC as a system, the data led to the conclusion that the probability is .95 that the true MTBF will not fall below 20,000 hours.

The interpretation of these results is important. The values given for MTBF do not represent expected lifetimes. The low limit MTBF of 20,000 hours for the complete OEC unit implies that at a confidence level of .95, no failures will occur within the complete unit before it has logged 20,000 hours of operating time. Hence, the majority of OEC units can be expected to operate at least 20,000 hours before a failure requiring corrective maintenance occurs.

2.1.6 Arctic Compatibility

OEC units have accumulated many hours of successful operation under environmental conditions similar to those which will be experienced on the Enhanced DEW Line. Currently, OEC units are operating in Arctic conditions in Alaska, Sweden, and Greenland.

There are currently 108 OEC units deployed along the Trans-Alaskan Oil Pipeline providing prime power and emergency backup power for remote gate valves and communications equipment. These units are designed to withstand seismic loads of 8.5 on the Richter scale, snow loads to 90 psi, winds up to 95 mph, ambient temperatures down to -76°F, with all conditions occurring simultaneously. Thus, there would be no need for further development for Arctic operation as the OECs have demonstrated Arctic compatibility.

2.1.7 Maintenance

Scheduled maintenance on the OEC consists primarily of burner cleaning at six-month or one-year intervals (depending on the type of fuel being used), annual replacement of the thermocouple (and burner nozzle for a diesel-fired unit), and cleaning of the condenser fins. The remaining tasks are basically visual inspections and performance checks, including checks for loose wires, bolt and seal tightness, vacuum level, and control system performance.

This maintenance routine can be performed by electronic technicians briefed in the operation of the OEC, thereby eliminating the need for highly skilled or specialized maintenance personnel dedicated to the power generation system.

Concerning spare parts, Ormat Systems recommends purchase of a spare parts package. Because of the high reliability of the system, it is not likely that all types of spares will be required for every unit deployed (with the exception of the thermocouple and burner head). Hence, the quantities of each type of spare part within the package are sized based on the expected requirements, given the number of units purchased. Spare parts in the package are for the combustion system and electrical panel.

It should also be noted that the OEC is designed for a twenty-year service life without equipment overhaul or subsystem replacement.

2.1.8 Operational Experience

As an aid in evaluating the OEC as a potential source of prime power for SEEK FROST unattended radars, the list of OEC users was referenced in an attempt to identify an application of the OEC which was similar to the SEEK FROST scenario. The intent was to find OEC units deployed in a remote Arctic environment as unattended prime power generators, and which required fuel storage and refueling visits.

An application which satisfies these conditions and closely parallels the use of the OEC being considered for SEEK FROST is the deployment of OEC units along the Trans-Alaskan Oil Pipeline. There are currently 108 of the 600-watt OECs being used as unattended power sources for remote controlled, electrically operated gate valves and for communications and supervisory equipment. The gate valves are selectively opened and closed by VHF radio from the operations control center in Valdez, Alaska. These units were installed during the spring of 1976 and have been in the operating mode since late summer 1976.

Specifically, two 600-watt, propane-fueled OEC units at each of forty-six sites serve as direct power supplies to switching and control equipment, supervisory equipment, radios, displays, and are used to charge batteries which deliver power for gate valve shut-down. In addition, heat is supplied by the OEC units to the buildings to maintain an interior temperature no lower than 41°F. The units operate in a load-sharing mode, with each unit capable of carrying the full station load upon a failure of the other unit. At sixteen other sites in the southern end of the pipeline, a single OEC serves as a backup to commercial power.

Through conversations with various personnel who were involved with the selection of the OEC as a power generator for the remote stations, issues have been raised which will have to be considered for the SEEK FROST application.

One such issue was the choice of a fuel source for the OEC units. The final decision to use propane fuel was made for two primary reasons: (1) the propane units are simpler and cheaper to maintain than diesel-fired units, and (2) propane presents few environmental problems associated with leaks or spills during refueling.

Next came considerations concerning storage facilities for the propane fuel. Storage tanks above ground were considered undesirable due to the ambient temperatures of the Arctic environment. Specifically, if the liquid propane, delivered to the sites by truck in pressurized tanks, falls below -30°F, the vapor pressure loss is significant enough to require pumping from the storage tank to the burner.

It was decided to bury the storage tanks (10,000 gallon capacity) six feet underground, as the thermal characteristics of the soil rarely allow the soil temperature at this depth to fall below 32°F. Thermostat-controlled heaters provide heat to the storage tanks to maintain sufficient vapor pressure such that pumps are not required to transfer fuel from the tanks to the burner.

Similar considerations will be necessary should other types of fuels be desired. DEW Line personnel have raised the issue of the effects of the Arctic environment on fossil fuels, such as JP-4, JP-8 or commercial Jet A-1. They feel there is a potential freeze problem with fuel stored in small tanks (less than 1000 gallons) and transferred through small pipelines (less than one inch) if the freeze point of the fuel is greater than -60°F. Hence, this issue should be addressed for the SEEK FROST application as similar complications may arise.

Maintenance requirements for the OEC units deployed along the pipeline were also investigated. Operations personnel from the Alyeska Pipeline Service Company, which is responsible for operating and maintaining the pipeline, indicated that to date there is no organized data collection and storage scheme concerning the maintenance actions required for the OEC units or the cost associated with their upkeep. However, they did relate information concerning the maintenance concept for the units and their impressions of the performance of the OEC units thus far.

As mentioned, the remote stations to which the OECs supply prime power contain control, supervisory, and communication equipment, and battery systems which are charged to supply the power to operate the gate valves. The station status is monitored at manned pump stations, each of which monitors the status of several remote sites. Sensors at the pump stations identify problems at the stations only as electrical or mechanical. Gauges and meters which supply information concerning the operational status of the remote stations, including the OEC units, are located only at the remote stations. Thus, remote monitoring of the OEC status is not performed.

When a problem is detected at a remote station, maintenance teams are dispatched to the troubled station to isolate the fault. Transportation is by motor vehicle when feasible, otherwise by helicopter.

From this description, it is apparent that the maintenance concept being used on the pipeline is not dissimilar from that being envisioned for the SEEK FROST system.

Concerning the performance and reliability of the OEC units thus far, Alyeska personnel indicated that after approximately three years of operation, the OECs have performed quite well and have been perhaps the most reliable pieces of equipment involved in the entire pipeline operation. After minor problems during hookup and integration, the units have required little attention and minimal maintenance. Only one unit has required replacement due to a defect in cable insulation.

At the sixteen sites where the OEC units serve as emergency backup power systems to commercial power, the performance has also been reliable. Frequent icing conditions have caused several commercial power outages and to date the standby OEC units have responded without startup problems.

Preventive maintenance has consisted of periodic inspection and performance checks during maintenance visits for other station equipment. Burner cleaning, thermocouple replacement and performance checks are done each year during refueling visits. In most units, the original burners are still in use and functioning as required.

Corrective maintenance has also been minimal. While not able to identify the exact causes of OEC failures from memory, Alyeska personnel mentioned a few isolated cases in which one of the two units at a station went down and required a maintenance visit. (Ormat Systems personnel have indicated that four units have failed to date.) At least one case involved problems with fuel transfer and not the OEC itself. In all cases, except the unit requiring replacement, the problems were minor and the units were back on-line in a short period of time. Also of importance, upon failure of the units, the automatic switching of the station load to the redundant unit functioned properly. Hence, there was no station down-time attributable to prime power outage.

Refueling at the remote stations is performed once per year. Liquid propane fuel is delivered by truck to the 10,000 gallon capacity storage tanks. A similar refueling schedule is envisioned for the SEEK FROST system, with helicopter shuttle replacing truck transport.

In summary, several people who took part in the planning of the remote station's prime power generation and others who are currently involved with the operation of the pipeline were contacted concerning various aspects of the OEC. Based on their reactions, it appears that their expectations concerning cost, installation schedule, performance, reliability, and fuel consumption have all been met.

2.1.9 Fuel Consumption

As mentioned previously, the OEC is capable of operating on a variety of fuels. Currently, diesel fuel is the most widely used fuel, with propane being the second most popular choice. While propane is a cleaner burning fuel which allows longer intervals between combustion system cleaning and replacement, it does present minor additional problems in transport and handling due to the need for

pressurized containers. The desirability of nuclear isotope fuels has also been adversely affected by increased safeguards and restrictions in handling.

From a logistics standpoint, it would be desirable to keep the types of different fuels required on the DEW Line to a minimum. The presence of diesel engine-generator sets currently on the line necessitates diesel fuel being procured and transported to the sites. Also in use on the DEW Line is JP-4 jet fuel (a high-grade kerosene), used in both fixed-wing aircraft and helicopters. Using JP-4 as a fuel for the OEC would eliminate the need for diesel fuel and hence simplify the logistics task associated with fuel resupply.

Based on the above considerations, both JP-4 jet fuel and propane will be examined in detail as they appear to be the most likely candidates for the OEC fuel. While propane may present minor new logistics considerations, these must be weighed against its advantages previously documented.

Representatives from Ormat Systems have provided fuel consumption rates for the Ormat Hybrid Turbogenerator System described in Section 2.1.5. The propane-fueled system will consume approximately 7.04 pounds per hour while providing a 5 KW load. Operating on jet fuel, the system will consume about 7.25 pounds per hour at 5 KW. Noting that fuel consumption for the OEC is basically linear with respect to load, these consumption rates will be twice as high when the system is running at 10 KW during maintenance visits.

Consistent with the maintenance philosophy adopted for the SEEK FROST UAR Stations, the assumption is made that the 10 KW load for maintenance visits will be required no more than 15 days (360 hours) per year. This includes allowances for weather delays and any other unforeseen circumstances. Based on this assumption, the annual fuel consumption, FC, for a UAR Station powered by the hybrid OEC system is computed as:

$$\begin{aligned} FC = {} & (\text{No. hours at 5 KW}) \times (\text{fuel consumed at 5 KW in lb/hr}) \\ & + \\ & (\text{No. hours at 10 KW}) \times (\text{fuel consumed at 10 KW in lb/hr}) \end{aligned}$$

The annual fuel consumption for the OEC-powered UAR Station is as follows:

Hybrid OEC using propane: FC = 59,125 + 5080 = 64,215 lb/yr

Hybrid OEC using jet fuel: FC = 60,900 + 5220 = 66,120 lb/yr

These consumption rates will serve as inputs to cost calculations for fuel and fuel transport as part of the LCC Model.

2.1.10 Life Cycle Costs

The LCC Model used for estimating the acquisition and ownership costs of the OEC is given in Section 1.5. The operational lifetime of the OEC power generating system is twenty years. The inputs to the model and their source/justification are given below for each cost element.

2.1.10.1 Development. The OEC is currently capable of supplying from 200 to 6000 watts of rectified DC power on a continuous basis, operating unattended for periods of six to twenty-four months, with a useful service life of twenty years. The OEC has demonstrated capability of Arctic operation. Therefore, no development costs would be incurred for the SEEK FROST application of the OEC as an unattended prime power source.

2.1.10.2 Procurement. The cost of the Ormat Hybrid Turbogenerator System described in Section 2.1.5 was quoted as $100,000 by Ormat Systems representatives in March 1979. This system is fully integrated and tested, and ready for field installation and operation in the Arctic.

For a propane-fueled OEC system, special pressurized storage tanks would be required, similar to the tanks used on the Alaskan Pipeline. The cost of a 15,000 gallon pressurized tank (which would allow almost 2000 gallons as a safety margin should refueling be delayed) would be approximately $12,000. Further investigation of meteorological conditions would be required to determine if conditions would necessitate these tanks being placed underground. In any case, the cost of the tank would remain unchanged. (See Section 2.1.9 for a discussion of underground storage tanks.)

For jet fuel storage, a specially-lined 15,000 gallon storage tank would cost approximately $6400. Three cradle-like supports on which the tank would be placed would cost approximately $800, giving a total cost of $7200.

2.1.10.3 Installation. Information concerning the cost of site preparation, shipping the power system to the site, and installation and check-out at the site comes from the GE Study[1] and from manufacturer's quotes. The reader is referred to the referenced GE Study for a detailed breakdown of the costs taken from that source.

Remote site preparation (Arctic environment) is reported in the GE Study at a cost of $60,000.

Shipment of the OEC units is assumed to be by truck from Hopkinton, Mass. to the ports of Montreal, Quebec and Seattle, Wash. From these ports, the units are taken by ship to the remote sites (helicopter airlift from the ship when necessary) for installation. The cost of truck transport to Seattle is used here as it is the more expensive option. For the 5 KW hybrid system, shipment to Seattle is quoted at $875 by Ormat personnel. Cost for shipment by ship to the site and helicopter airlift from ship to site is given in the GE Study as $450 per ton. At a weight of approximately 7000 pounds, an average cost of $1600 is assumed. Installation at the site can be accomplished by two men (electronic technician skill level) in two days. The operation essentially consists of placement and fastening of the module, connecting the fuel transfer system, chimney stack installation, and load connection. The installation is performed by Ormat Systems personnel at a cost of approximately $1000. Thus, the total cost for this cost element is estimated to average $63,500.

Note that the cost of installation as defined here is dominated by the cost of remote site preparation. At sites with existing facilities, this cost can be expected to be significantly smaller. For this report, the site is assumed to be new and hence incur the $60,000 cost given in the GE Study.

2.1.10.4 Maintenance. Maintenance requirements for the OEC are outlined in Section 2.1.8. Combustion system cleaning and parts replacement will not require a dedicated maintenance visit for this purpose. The amount of time required for these tasks should be on the order of only a few hours per year; hence the cost of labor for maintenance can be considered to be a nominal $100 per year. Ormat Systems representatives estimate a spare parts cost (see Section 2.1.8 for

spares requirements) of approximately 3% of the units acquisition cost for a period of five years. At $100,000 per unit, this results in an estimated annual spares cost of approximately $600 per unit. This gives an estimated annual maintenance cost of $700. In addition, the OEC units require no overhaul for a service life of twenty years. (Note: Although the propane-fueled unit will not require burner cleaning or replacement as often as the OEC units operating on jet fuel, this maintenance cost differential is small and is assumed negligible.)

2.1.10.5 Fuel (FC). The cost of fuel for the OEC will be calculated for both propane and jet fuels as these are the two most likely candidates for the SEEK FROST Program. The calculations will be based on the consumption rates of the OEC computed in Section 2.1.10 and on current prices for propane and JP-4 jet fuel.

The most recent purchase of jet fuel for the DEW Line (summer 1979 resupply) was at an average price of $.78 per gallon delivered to the sites by sealift from Seattle, Washington, and Montreal, Canada (no helicopter shuttle). This fuel is for Arctic applications with a freeze point of -70°F. At a consumption rate of 66,120 pounds per year, which, at 6.50 pounds per gallon is equivalent to 10,170 gallons per year for the OEC operating on jet fuel, the annual cost of fuel is given by:

FC(JP-4 jet fuel) = 10,170 gal/yr x $.78/gal = $7935/yr

As mentioned in Section 1.5.1, the average price of $.78 per gallon for jet fuel includes sealift transportation (barge or tanker) costs of $.28 per gallon. At 6.5 pounds per gallon for jet fuel, this converts to $.043 per pound for the sealift operation. Using this sealift transportation cost, a cost per gallon for propane sealift transport can be computed. Using 4.25 pounds per gallon for propane, the sealift cost to the current sites would be $.18 per gallon.

The purchase price of propane is currently quoted at $.92/gallon, which, when adding in the cost of the sealift of $.18 per gallon, results in a unit cost of $1.10/gallon for propane. The propane-fueled OEC consumes 64,215 pounds, or equivalently, 15,110 gallons of propane per year, giving the following annual cost of fuel:

FC(propane) = 15,110 gal/yr x $1.10/gal = $16,620/yr

2.1.10.6 Fuel Transportation (FT). The helicopter shuttle operation between the resupply vessel and the UAR site storage tanks that is assumed for this report is described in Section 1.5.2. Based on this scenario, an estimate of the cost of the helicopter shuttle will be made for each of the two quantities of fuel being considered.

It is assumed that the helicopter shuttle will be performed using the Sikorsky S-61, which is a candidate helicopter being considered for the SEEK FROST logistics and maintenance tasks. The data contained in the previously referenced report on helicopter support indicates that the S-61 has a cargo sling capacity that will allow transport of 5000 pounds of fuel per trip. The charge for the helicopter flight time is $1000 per hour. The fixed charge for the helicopter of $100,000 per month will not be included in the cost of fuel transport to the UAR sites as this task is only one of many that the helicopter will perform. Hence, no attempt is being made to pro-rate this fixed cost to specific tasks.

The OEC operating on jet fuel consumes 66,120 pounds per year at the UAR sites. Based on a helicopter capacity of 5000 pounds of fuel per trip, this gives a requirement for 14 trips from the resupply vessel to the site.

Using the time factors given in Section 1.5.2, each round trip from the vessel is assumed to require an average of twenty minutes. Thus, the entire site refueling operation will require

$$14 \text{ trips} \times 1/3 \text{ hr/trip} = 4.66 \text{ hours}$$

of helicopter flight time. At $1000 per flight hour, the average cost of helicopter flight time is $4660 for the refueling of the UAR sites.

The cost per flying hour for the helicopter includes the cost of the flight crew (pilot and co-pilot). Therefore, in computing the cost of personnel required for the refueling operation it is necessary to account for the four support personnel mentioned in Section 1.5.2 (two personnel for sling hook-up and two personnel to transfer fuel to the storage tanks). Assuming a charge of $20 per hour for contractor support personnel (based on average costs for current DEW Line personnel) and assuming that they will be utilized for an eight hour period for the refueling of an UAR site (includes preparation time, time en route, etc.), the average cost of the additional support personnel is $640. This gives a total cost of the shuttle operation of FT = $5300 for jet fuel required by the OEC.

Adding the cost of the fuel computed previously to the helicopter shuttle cost gives the following total cost to supply jet fuel to a UAR site: FC + FT = $13,235. This results in an average unit cost of delivered jet fuel of $1.30 per gallon, or $.29 per KWH.

The computation of the helicopter shuttle cost for propane is done in the same manner as above. The propane-fueled OEC has a per site requirement of 64,215 pounds per year. This amount of fuel would require 13 trips to the site by helicopter. The helicopter flying time is then

$$13 \text{ trips} \times 1/3 \text{ hr/trip} = 4.33 \text{ hours.}$$

At a rate of $1000 per flight hour, the helicopter cost comes to $4330 for each UAR site. Adding the cost of additional support personnel of $640 (again assuming an eight hour utilization period) results in a total shuttle cost of FT = $4970.

Adding the cost of fuel and fuel transport gives the following total cost of supplying propane fuel to a UAR site: FC + FT = $21,590. This results in a unit cost of delivered propane of $1.43 per gallon, or $.47 per KWH.

Alyeska personnel report a cost of $1.25 per gallon of propane delivered to the OEC units at remote gate valve sites along the Trans Alaskan Pipeline. The fuel is transported to the sites by truck during resupply runs each summer. Considering the additional distance the resupply vessels must travel to reach the DEW Line sites and the high cost of helicopter transport versus truck transport, the projected cost of $1.43 per gallon computed above does not appear unreasonable. Hence, the cost estimating methodology used for the helicopter shuttle operation may be considered a reasonable model to employ given the information available.

The results of the fuel cost and fuel transport cost computations are summarized in Table 1 below. Table 2 contains on-site delivered costs of fuel broken out as purchase, sealift, and helicopter shuttle in order to identify the cost drivers associated with each type of fuel. This table indicates that although propane is more expensive to purchase, its weight makes it a more economical fuel to transport by sealift and helicopter shuttle.

TABLE 1

Annual Fuel and Fuel Transportation Costs for Jet Fuel and Propane

Required for OEC-Powered UAR Sites

	Unit Cost of Fuel(1) (Purchase + Sealift)	Annual OEC Consumption	Fuel Cost (FC)	Helicopter Cost	Support Personnel Cost for Shuttle	Total Shuttle Cost (FT)	Delivered Cost of Fuel(4)
JP-4 Jet Fuel	$ .78/gal	10,170 gal(2)	$ 7935	$4660	$640	$5300	$.29/KWH
Propane	$1.10/gal	15,110 gal(3)	$16,620	$4330	$640	$4970	$.47/KWH

(1) See Section 1.5.1 for discussion of unit cost of fuel

(2) 6.50 pounds per gallon

(3) 4.25 pounds per gallon

(4) Load of 5 KW for 8400 hrs/yr = 42,000 KWH
Load of 10 KW for 360 hrs/yr = 3,600 KWH

Total annual energy requirement = 45,600 KWH

TABLE 2

Per Cent of On-Site Delivered Cost of Fuel Attributed to

Purchase, Sealift, and Helicopter Shuttle

For Ormat Energy Converter

	% Due to Purchase	% Due to Sealift	% Due to Helicopter Shuttle
JP-4 Jet Fuel	38% ($.50/gal)	22% ($.28/gal)	40% ($.52/gal)
Propane	64% ($.92/gal)	13% ($.18/gal)	23% ($.33/gal)

2.1.11 Life Cycle Cost Summary

The life cycle costs associated with the acquisition and ownership of the 5 KW Ormat Hybrid Turbogenerator System are given in Table 3.

The out-year costs associated with fuel and other ownership costs should be considered to be in current year dollars, as the unit costs of fuel and labor are based on current quotes.

2.1.12 Fuel Selection

It should be noted that the versatility of the OEC with respect to a fuel source and the ease of converting from one type of fuel to another will allow for selection of a fuel (even after deployment) which will minimize the cost associated with fuel purchase and transport. To provide an example of the type of analysis which will be required in choosing a fuel, Figure 3 shows how the preference for jet (or diesel) fuel over propane is related to its cost. Similar analysis for other types of fuel, including types that are currently being developed as alternatives to petroleum products, could also be performed. Other issues, such as availability and logistics considerations, should also be addressed before a final selection is made.

2.1.13 Outlook

R&D programs are currently being conducted by Ormat Turbines Ltd. of Israel, manufacturer of the Ormat Energy Converter. The programs are aimed primarily at increasing the efficiency of the OEC and reducing its size and weight. Of particular interest to the SEEK FROST Program is the development of an improved 5 KW OEC unit which will achieve an electrical energy efficiency of 15% (current electrical efficiency is 7%) when supplying a 5 KW load. When combined with another 5 KW unit in the hybrid configuration described in Section 2.1.5, the electrical efficiency is projected at 21% for the entire system.

The impact of the improvement in efficiency on fuel consumption will be significant. Applying the methodology of Section 2.1.10 for computing fuel consumption rates, the following quantities of fuel would be required for the improved 5 KW hybrid system:

Propane:	34,350 lb/yr
JP-4 jet fuel:	34,655 lb/yr

TABLE 3

Life Cycle Cost Summary for 5 KW Ormat Hybrid

Turbogenerator System at a UAR Site(1)

(FY79 Dollars to Nearest $100)

	Acquisition		O&M				
	Procurement(2)	Installation(3)	Maintenance (Parts + Labor)	Fuel(4)	Fuel Transportation	20-year O&M(5)	Per-site LCC(5)
Ormat System Using Jet Fuel	$107,000	$63,500	$700/yr	$ 7900/yr	$5300/yr	$278,700	$449,200
Ormat System Using Propane	$112,000	$63,500	$700/yr	$16,600/yr	$5000/yr	$445,800	$621,300

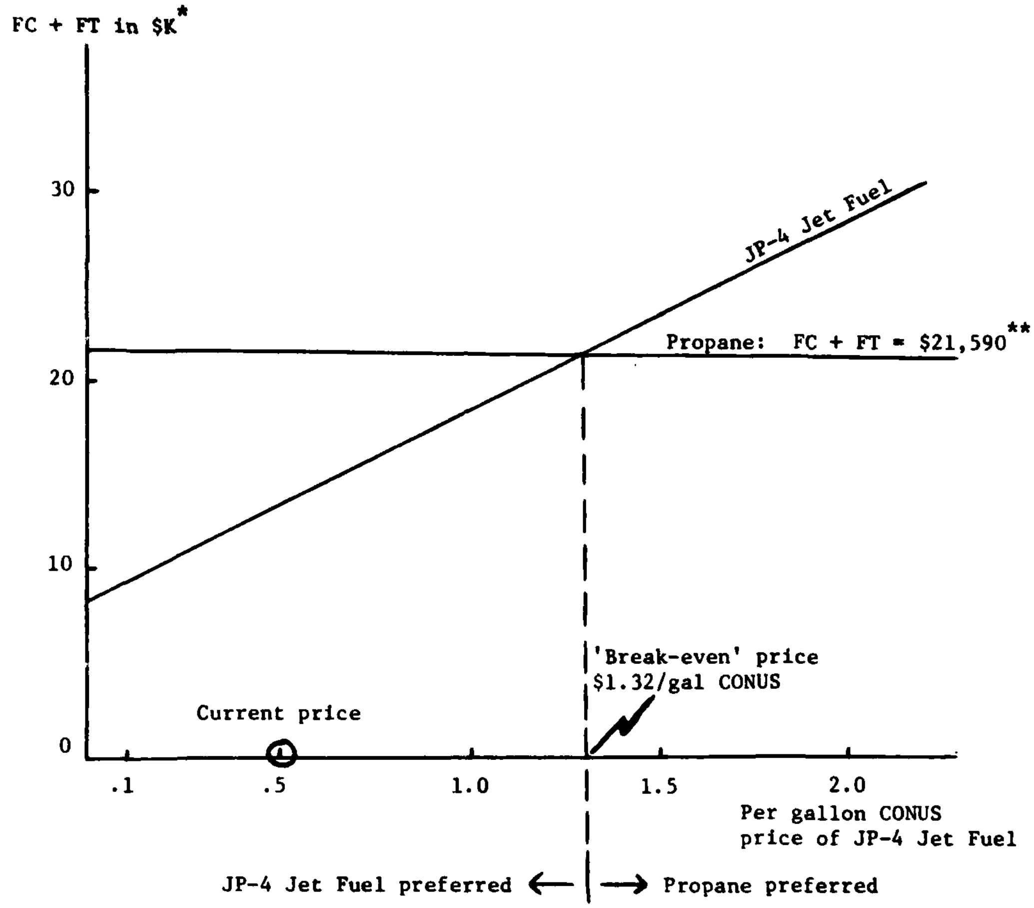
(1) No development cost is required for this system (see Section 2.1.5)

(2) Includes OEC unit ($100,000) and cost of 15,000 gallon fuel storage tank (see Section 2.1.4 and 2.1.11.2 for configuration being costed)

(3) Includes new site preparation, shipment of system to the site, installation and check-out at site

(4) Based on current prices

(5) See Section 1.5 for description of LCC equation



*Assumes sealift and helicopter shuttle costs are independent of CONUS price and, therefore, are held constant

**Assumes propane price of $.92/gal CONUS (see Section 2.1.11.5)

Figure 3. Analysis of Fuel Cost for Ormat Energy Converter Operating on Propane and JP-4 Jet Fuel

Referring to Section 2.1.10, it can be seen that the fuel requirements for the improved system will represent an average annual savings in fuel of nearly 50% over the OEC units which are currently available. At current prices this would represent an annual savings of approximately $7,730 for the propane-fueled OEC, and $3775 for the OEC operating on jet fuel. In addition, the cost of fuel transportation will decrease to approximately $3000, as compared with the fuel transportation costs in Table 1.

The development schedule supplied by Ormat Turbines Ltd. indicates that the improved 5 KW units will be available in twenty-four months, approximately August 1981. Even with moderate delays in schedule, these improved units should be available in time for procurement for SEEK FROST.

R&D personnel at Ormat Turbines Ltd. have indicated that there would be no development cost to the U.S. Air Force for the development of the improved units as the programs are being funded by the company itself. Also, the acquisition cost will remain approximately the same at $100,000 for the 5 KW hybrid system.

In addition to the improved 5 KW unit, development of a 60 KW unit is also scheduled for completion in twenty-four months. The electrical efficiency of this unit is projected at 22%, with a projected sale price between $80,000 and $100,000, depending on quantity and other factors. The possibility of a need for a 60 KW unit is discussed in Section 3.1.

2.1.14 Summary for Ormat Energy Converter

The Ormat Energy Converter has many features which make it desirable as a prime power source for the SEEK FROST unattended radar stations. In addition, the development work currently being performed will result in an even more attractive system at no additional development cost to the U.S. Air Force. Below are some of the key features of the Ormat system:

- Heat source versatility which allows selection of a least-cost fuel
- Proven high reliability
- Demonstrated Arctic compatibility
- Minimal, infrequent maintenance requirements

- Ease of installation
- No overhaul required over 20-year operating lifetime
- Significant improvements in efficiency forecast prior to scheduled SEEK FROST deployment
- No development cost to U.S.A.F. for improved OEC units

Two features of the OEC which adversely effect its desirability as a UAR station prime power source are:

- High acquisition cost
- Low electrical energy efficiency resulting in high costs for fuel and fuel transportation

These features of the system will be discussed further in Section 4.0.

2.2 FUEL CELL POWER PLANTS

The information contained in this section concerning the application of fuel cells as unattended prime power sources for the SEEK FROST Program is based primarily on conversations with representatives from the Energy Research Corporation (ERC) of Danbury, Connecticut and the GE Unattended Power Systems Study.(1) Also contributing were representatives from the United Technologies Corporation (UTC) Power Systems Division of South Windsor, Connecticut. Both companies are actively involved with the development of fuel cells ranging in output from 1.5 KW to several megawatts.

2.2.1 Description

A fuel cell power plant is a galvanic engine which, in the presence of an electrolyte, converts chemical energy into electrical energy. The capacity of the fuel cell is limited only by the supply of fuel, commonly referred to as the reactant. The fuel cell is characterized by high thermal efficiency, low maintenance, silent operation, and the absence of pollutant emissions.

The fuel cell power plant is comprised of four major subsystems: (1) the catalytic hydrogen generator, or reformer section, which processes the hydrocarbon fuel, (2) the phosphoric acid fuel cell stack, made primarily from carbon and graphite, which converts the processed fuel and air into DC power, (3) the power conditioner, which accepts raw DC power from the fuel cell stack and converts it to a regulated DC or AC output (depending on the needs of the user), and (4) the automatic control system (microprocessor-controlled), which provides the capability for automatic startup and shutdown, and response to load changes. A schematic of the integrated subsystems is shown in Figure 4.

2.2.2 Operation

The overall process through which DC power is generated is shown in Figure 5. In the reformer, the fuel, which may be most any hydrocarbon fuel, is processed in the presence of steam, heat and a catalyst (zinc-copper oxide and nickel-based catalysts are two common types). This process is referred to as steam reforming, and results in a hydrogen-rich gas, approximately 75% hydrogen. The remaining products are carbon monoxide and carbon dioxide, which are essentially exhausted from the system.

The processed fuel passes from the reformer to the fuel cell stack where it is combined with air to be converted to useable DC power. In this process, molecules of the hydrogen gas break down into hydrogen ions and electrons at the negative electrode of the stack. The electrons collect at the electrode while the ions drift through the electrolyte (phosphoric acid is common) to the positive electrode. Here they combine with oxygen and electrons to form water. A simplified version of this process which produces DC power and water is shown in Figure 6.

Referring again to Figure 5, note that the water by-product is cycled back through the system as steam and is used in the reformer. Because of the water-producing reaction, there is no need for water to be resupplied to the fuel cell site.

2.2.3 Status

The majority of the research and development work on fuel cell power plants of a size applicable to the SEEK FROST Program has been sponsored by the U.S. Army Mobility Equipment R&D Command. This work has thus far led to the initial development of a 1.5 KW fuel cell power plant capable of operation on a variety of fuels, including

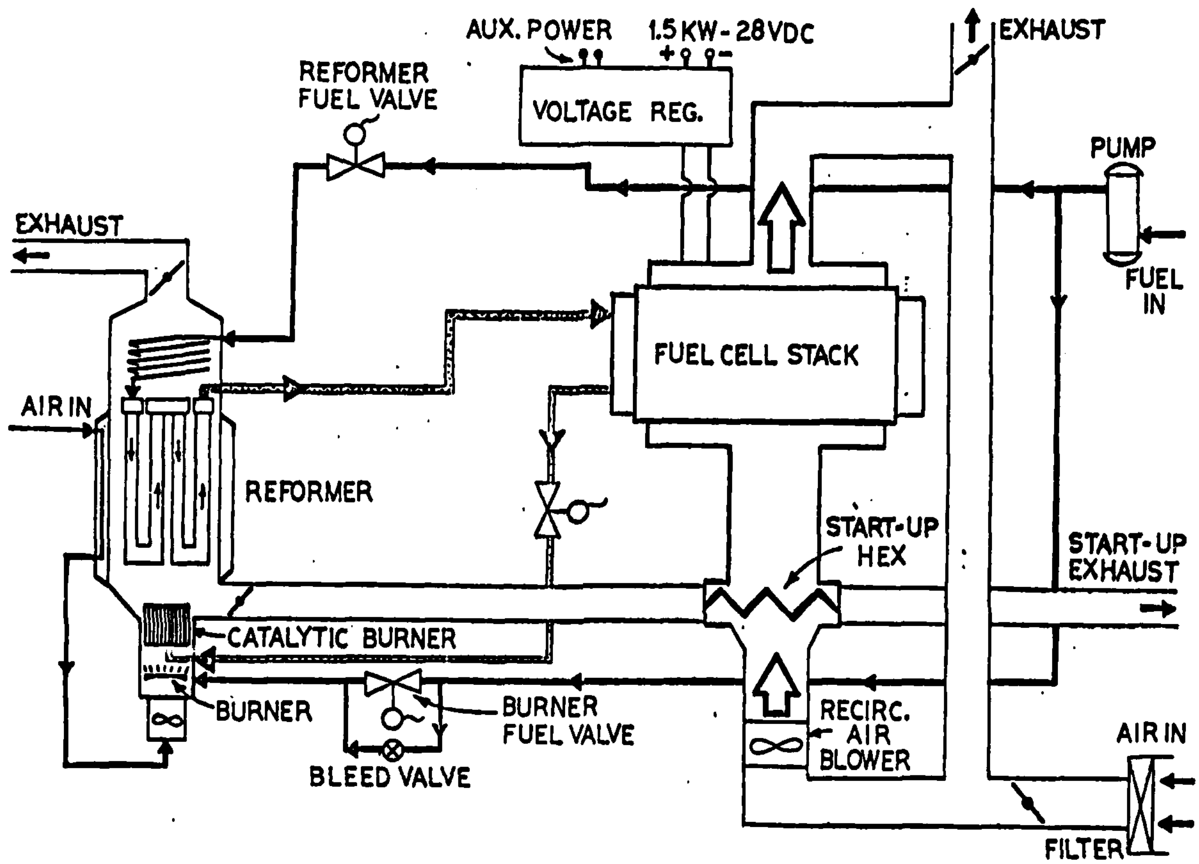


Figure 4. Fuel Cell Power Plant Integrated Subsystems

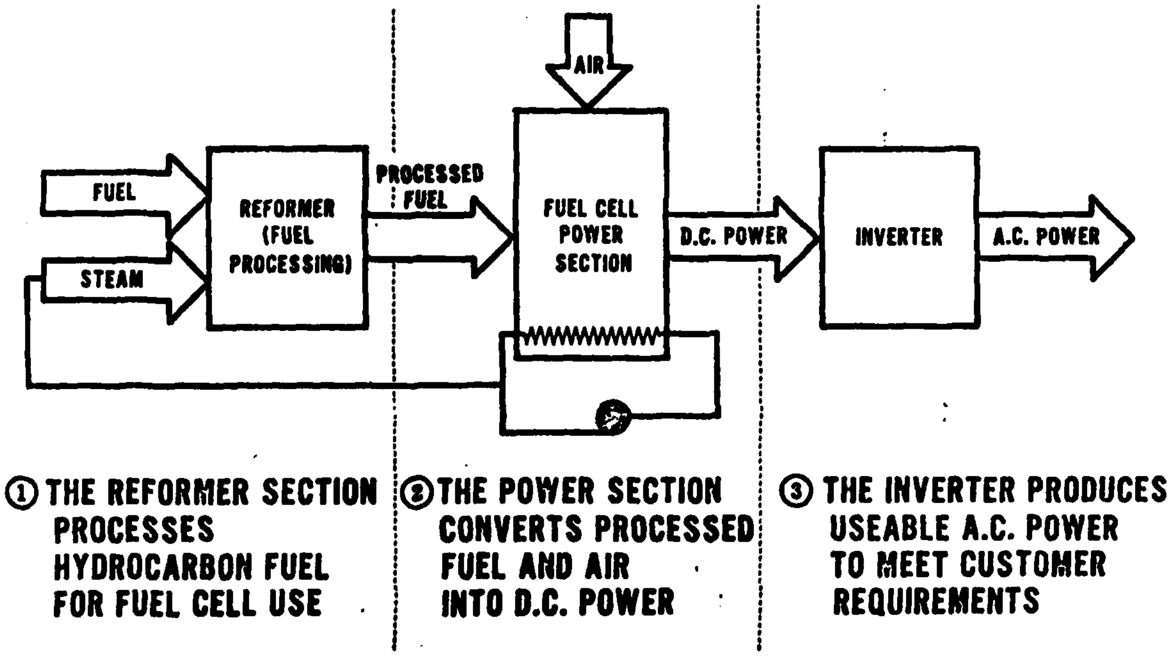


Figure 5. Fuel Cell Power Plant Operation

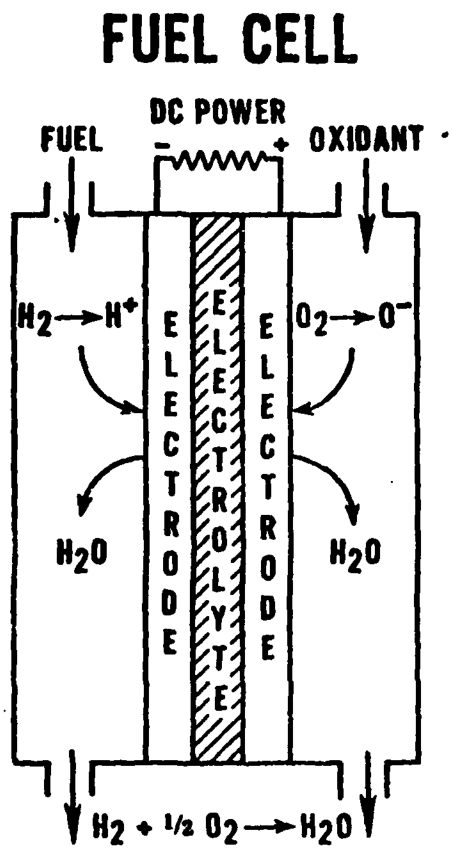


Figure 6. Fuel Cell Reactions Producing DC Power

hydrogen, methanol, and methane. The program is progressing into full-scale development of 3 KW and 5 KW units, and production of the initial lot of 5,000-10,000 units is scheduled for the late 1983 - early 1984 time frame.

Representatives from ERC have indicated that the fuel cell power plants being developed for the Army could be used for the SEEK FROST application. In fact, the Air Force requirements are far less stringent than those in the Army specification. Among the requirements for the Army program which will tend to drive the cost of the development effort are: (1) size and weight constraints: the 5 KW unit is required to be at most 18 cubic feet in volume and 500 pounds in weight; (2) portability: the Army's requirements call for a portable power plant that can withstand frequent truck transport; and (3) frequent startup: the power plant must be capable of 2000 startups per month.

The requirements given above would not apply to the SEEK FROST Program, as the fuel cell power plant would be a stationary, continuously operating unit with no practical size limitations. Hence, the development program for the SEEK FROST application would be far less costly than the development program being planned for the Army. In any case, representatives from both ERC and UTC feel that the requirements for the SEEK FROST application of the fuel cell power plant are attainable and procurement of the units could be realized by 1984.

2.2.4 Fuel

The fuel cell power plant can be designed to operate on a variety of hydrocarbon fuels. Pentane is considered a desirable fuel because of its relatively high BTU content and because it is easily processed to hydrogen-rich gas. Methal, a methanol-alcohol mix, is also an attractive alternative as it is clean and also is easily reformed to a hydrogen-rich gas. The cost and availability of these fuels and the willingness of the Air Force to introduce a new fuel into their inventory will impact the choice of a fuel.

Jet fuel, such as JP-4, is also a candidate for the fuel cell power plant, but the high sulfur content of this type of fuel would require it to be preprocessed before being used in the reformer. High sulfur content in the fuel is undesirable as the sulfur collects on the catalyst in the reformer and inhibits its ability to react. This degradation of the catalyst will have an adverse affect on the maintenance interval and hence, the cost of maintaining the system (i.e., more frequent catalyst replacement will be required.)

Power required for the desulfurization process will cause the overall efficiency of the system to be reduced.

2.2.5 Configuration

To meet the SEEK FROST UAR station load requirement of 5 KW during unattended operation and 10 KW during periods when maintenance teams are on-site, two 5 KW fuel cell power plants will be required, each supplying one-half of the station load. The design of the fuel cell power plants provides for automatic response to changes in load as the fuel feed rate to the reformer is proportional to stack load current. Therefore, upon failure of one unit, the control system will transfer the full load to the other unit automatically.

The primary reason for suggesting the configuration described above, which utilizes two 5 KW units at half load, is to take advantage of an interesting operating characteristic of the fuel cell power plant. Unlike most systems, the peak efficiency for the fuel cell units does not occur at full load, but somewhere in the vicinity of 50% load. At this point, electrical efficiency of approximately 35-37% can be expected according to personnel contacted at ERC. Again, the efficiency will be adversely affected should a fuel be used that will require pre-processing due to high sulfur content, such as jet fuel. Fuel cell power plants requiring pre-processing are expected to achieve electrical energy efficiencies of approximately 30%.

2.2.6 Reliability

At this stage of development, sufficient test data has not been accumulated that will allow an accurate estimate of the reliability of the fuel cell power plant. However, representatives from both ERC and UTC feel that the reliability of the fuel cell power plant will far exceed the requirements of the SEEK FROST Program. With the configuration described in Section 2.2.5, it is assumed that the reliability of the fuel cell units will be consistent with the UAR station reliability goals.

2.2.7 Maintenance

The fuel cell power plant is being designed with a maintenance cycle of two and one-half years. The maintenance consists of: (1) fuel cell stack replacement, (2) reformer catalyst replacement, and (3) blower replacement. These tasks can be accomplished in a single day. In addition, routine checks of system performance and

visual inspection of the system can be made while maintenance personnel are on site (e.g., check gaskets, oil bearings.)

2.2.8 Operational Experience

As the fuel cell power plant of a size of interest for the SEEK FROST application is still in the development phase, no data concerning field operation with this type of system is available. Thus, performance characteristics and maintenance cycles must be considered as projections at this point.

2.2.9 Arctic Compatibility

No field operational data is available concerning fuel cell power plant performance in an Arctic environment. However, representatives from both ERC and UTC feel that no significant development effort will be required to design the power plant to withstand Arctic conditions.

2.2.10 Fuel Consumption

Fuel consumption rates for pentane and JP-4 are presented in this section. Pentane has been suggested by ERC representatives who feel it is well suited for the SEEK FROST application. JP-4 is given consideration due to its favorable effect on logistics tasks associated with fuel resupply. Thus, these two fuels are considered the most likely energy sources for the fuel cell power plant.

Section 2.2.5 described the power plant configuration as consisting of two fuel cell units each operating at one-half load. At this load, using a fuel which does not require pre-processing, the system can be expected to achieve electrical energy efficiency of approximately 37% (as opposed to approximately 35% at full load) according to ERC personnel.

Using pentane as a fuel, the fuel cell power plant is assumed to achieve an electrical efficiency of 37% while supplying a 5 KW UAR station load. Assuming a BTU content for pentane of 21,120 BTUs per pound, the fuel cell power plant is expected to consume approximately 2.18 pounds of fuel per hour. Operating in an unattended mode for 8400 hours per year, this results in a requirement of (8400 hr/yr) x (2.18 lb/hr) = 18,345 pounds of pentane per year to satisfy the 5 KW load requirement.

During the 360 hours per year which the UAR station load is assumed to be 10 KW, the two fuel cells are expected to operate at full load, causing the electrical efficiency to decrease slightly to approximately 35%. At this level of efficiency, the pentane fuel consumption is estimated at 4.62 pounds per hour, resulting in an additional requirement of (360 hr/yr) x (4.62 lb/hr) = 1,660 pounds of pentane annually. This gives a total annual pentane consumption of 20,005 pounds, or equivalently, at 5.26 pounds per gallon of pentane, approximately 3800 gallons.

As mentioned in Section 2.1.10, the use of JP-4 jet fuel would be desirable from a logistics viewpoint as it will be in use on the DEW Line for helicopter and fixed wing support aircraft. However, the high sulfur content of JP-4 would require pre-processing of the fuel before it enters the reformer, and hence the electrical energy efficiency of the power plant can be expected to decrease to approximately 28-30% (depending on load).

Given an electrical efficiency of 30% while supplying the 5 KW UAR station load, and assuming a BTU content of 21,540 BTUs per pound of JP-4 jet fuel, the fuel cell power plant is expected to consume approximately 2.64 pounds of jet fuel per hour. It is assumed that this comsumption rate will be required for 8400 hours per year, giving a requirement of (8400 hr/yr) x (2.64 lb/hr) = 22,185 pounds of JP-4 jet fuel annually for unattended operation.

During the 360 hours per year that the UAR station load is assumed to be 10 KW, the fuel cell power system is expected to operate at an electrical efficiency of 28%. This results in a consumption rate of 5.66 pounds per hour of JP-4 jet fuel. Therefore, an additional (360 hr/yr) x (5.66 lb/hr) = 2,035 pounds of JP-4 jet fuel will be required each year. This gives a total annual requirement of 24,220 pounds of JP-4 jet fuel, or, at approximately 6.50 pounds per gallon, an equivalent requirement of 3725 gallons per year.

The annual consumption rates computed above will serve as inputs to life cycle cost calculations concerning fuel cost and fuel transport cost.

2.2.11 Life Cycle Costs

The LCC Model used for estimating the acquisition and ownership costs of a fuel cell power plant is given in Section 1.5. The inputs to the model and their source/justification are given below for each cost element.

2.2.11.1 Development. As mentioned in Section 2.2.3, the U.S. Army is funding the bulk of the R&D program involved with the development of fuel cell power plants in the size range of interest for the SEEK FROST application. ERC representatives have suggested that the Air Force could withhold any official involvement in the R&D effort until the Army program has sufficiently progressed. At that point, the Air Force could sponsor a development program aimed specifically at the SEEK FROST application of fuel cell power plants. (The timing of this involvement would be consistent with the SEEK FROST deployment schedule.) Although the cost of such a development program could not be firmly quoted, ERC representatives feel that it would be in the area of two million dollars.

2.2.11.2 Procurement. The acquisition cost of the fuel cell power plant is subject to considerable uncertainty. The Army procurement plan will greatly decrease the unit cost of the system to the Air Force. The Army goal has been set at $1000 per KW; however, this is viewed by both ERC and UTC representatives as optimistic. Allowing a cost of $1500 per KW, the cost of the two 5 KW units would be approximately $15,000. Based on data from the GE Unattended Power Study[1], the cost of other equipment (shelter, control unit, batteries, tanks, etc.) would add an additional $35,000 to the unit cost of the system. Thus, a unit cost for the entire system would be on the order of $50,000 per site.

2.2.11.3 Installation. The installation costs are based on those contained in the GE Study and are estimated at $65,000.

2.2.11.4 Maintenance. The maintenance requirements and maintenance cycle are described in Section 2.2.7. ERC representatives have updated previous estimates of the maintenance requirements given in the GE Study. The updated estimates are: (1) fuel cell stack replacement: $2000; (2) reformer catalyst replacement: $200; and (3) blower replacement: $100. Labor costs for these tasks are estimated at $300 (3 men x 5 hours x $20/man-hour), giving a total cost of $2600. These actions are performed on a 2.5-year maintenance cycle, which gives an annual cost of $1040. Allowing for small replacement parts (bearings, gaskets, etc.), the annual maintenance cost is assumed to be $1100.

2.2.11.5 Fuel (FC). The cost of fuel required by the fuel cell power plant will be calculated for both pentane and JP-4 jet fuel as they are the most likely candidates for the SEEK FROST Program.

The consumption rates computed in Section 2.2.10 will be used, along with current prices for pentane and JP-4 jet fuel.

Referring to Section 2.1.11.5, the average cost of JP-4 jet fuel is assumed to be \$.78 per gallon delivered to the sites by sealift (no helicopter shuttle). At a consumption rate of 3725 gallons per year, the average annual cost of fuel for the fuel cell power plant operating on jet fuel is given by:

$$FC(\text{JP-4 jet fuel}) = 3725 \text{ gal/yr} \times \$.78/\text{gal} = \$2905/\text{yr}$$

To determine an average unit cost (purchase plus sealift) for pentane, reference is made to Section 1.5.1 where the cost of sealift transport was given as \$.043 per pound. At 5.26 pounds per gallon of pentane, this results in a sealift cost of \$.23 per gallon.

The purchase price of pentane is currently quoted at a bulk rate of \$.90 per gallon, giving an average unit cost of \$1.13 per gallon. At a consumption rate of 3800 gallons per year, the average annual cost of fuel for the fuel cell power plant operating on pentane is given by:

$$FC(\text{pentane}) = 3800 \text{ gal/yr} \times \$1.13/\text{gal} = \$4295/\text{yr}$$

2.2.11.6 Fuel Transportation (FT). The helicopter shuttle of fuel between resupply vessels and UAR sites is described in Section 1.5.2. Using the assumptions given for this type of operation, an estimate of the cost of the helicopter shuttle will be given for each of the fuels under consideration. Cost data relating to this operation is given in Section 2.1.11.6.

Operating with jet fuel as a fuel source, the fuel cell power plant is assumed to require 24,220 pounds of fuel annually for a UAR site. With a helicopter capacity of 5000 pounds of fuel per trip, 5 trips from the resupply vessel to the UAR site will be required.

The time factors given in Section 1.5.2 specify an average of twenty minutes for each round trip, giving a helicopter flying time requirement of

$$5 \text{ trips} \times 1/3 \text{ hr/trip} = 1.67 \text{ hours.}$$

At a rate of $1000 per flight hour, the average cost of helicopter flight time is estimated to be $1670 for the refueling of a UAR site.

Since the UAR sites powered by fuel cell power plants will require fewer helicopter trips, and therefore less time for the refueling operation, it is assumed that the support personnel will be required for only a four hour period for each site, as opposed to the eight-hour utilization period assumed in Section 2.1.10.6. Assuming a charge of $20 per hour for the four contractor-supplied support personnel, the average additional cost for the helicopter shuttle operation is assumed to be $320 for each UAR site. This results in an average annual fuel transportation cost of FT = $1990 for the jet fuel required by the fuel cell power plant.

Adding the cost of jet fuel computed in Section 2.2.11.5 to the transportation cost, the average total annual cost of supplying jet fuel to a UAR site is given by FC + FT = $4895. This results in an average unit cost of jet fuel delivered to a UAR site of $1.31 per gallon, or $.11 per KWH.

The computation of the cost of the helicopter shuttle of pentane is done in the same manner as above. The fuel cell power plant operating on pentane is assumed to require 20,005 pounds of pentane per year. This will require four trips to the site by helicopter, giving a flying time requirement of

$$4 \text{ trips} \times 1/3 \text{ hours/trip} = 1.33 \text{ hours.}$$

At a rate of $1000 per flight hour, the average cost of the helicopter flight time is assumed to be $1330 for the refueling of a UAR site. The additional cost of support personnel is again assumed to average $320 per site, giving an average total annual fuel transportation cost of FT = $1650 for the pentane required by the fuel cell power plant.

Summing the cost of fuel from Section 2.2.11.5 and the transportation cost gives the average total annual cost of supplying pentane to a UAR site: FC + FT = $5945. This results in an average unit cost of pentane delivered to a UAR site of $1.56 per gallon, or $.13 per KWH.

The results of the fuel cost and fuel transportation cost computations are summarized in Table 4 below. Table 5 contains on-site delivered costs of fuel broken out as purchase, sealift, and helicopter shuttle.

2.2.12 Life Cycle Cost Summary

The life cycle costs associated with the acquisition and ownership of a fuel cell power plant for the SEEK FROST UAR site are shown in Table 6. Again, note that the costs of fuel are based on

TABLE 4

Annual Fuel and Fuel Transportation Costs for Jet Fuel and
Pentane Required for UAR Sites Powered by
Fuel Cell Power Plants

	Unit Cost of Fuel[1] (Purchase + Sealift)	Annual Consumption	Fuel Cost (FC)	Helicopter Cost	Support Personnel Cost for Shuttle	Total Shuttle Cost (FT)	Delivered[4] Cost of Fuel
JP-4 Jet Fuel	$ .78/gal	3725 gal[2]	$2905	$1670	$320	$1990	$.11/KWH
Pentane	$1.13/gal	3800 gal[3]	$4295	$1330	$320	$1650	$.13/KWH

(1) See Section 1.5.1 for discussion of unit cost of fuel

(2) 6.50 pounds per gallon

(3) 5.26 pounds per gallon

(4) Load of 5 KW for 8400 hr/yr = 42,000 KWH
Load of 10 KW for 360 hr/yr = 3,600 KWH
Total annual energy requirement = 45,600 KWH

TABLE 5

Per Cent of On-Site Delivered Cost of Fuel Attributed to Purchase, Sealift, and Helciopter Shuttle For Fuel Cell Power Plant

	% Due to Purchase	% Due to Sealift	% Due to Helicopter Shuttle
JP-4 Jet Fuel	39% ($.50/gal)	21% ($.28/gal)	40% ($.53/gal)
Pentane	57% ($.90/gal)	15% ($.23/gal)	28% ($.43/gal)

TABLE 6

Life Cycle Cost Summary for Redundant 5 KW

Fuel Cell Power Plant at a UAR Site[1]

(FY79 Dollars to Nearest $100)

	Acquisition		O&M				
	Procurement[2]	Installation[3]	Maintenance (Parts + Labor)	Fuel[4]	Fuel Transportation	20-year O&M	Per-site LCC[5]
Fuel Cell Using Jet Fuel	$50,000	$65,000	$1100/yr	$2900/yr	$2000/yr	$119,900	$234,900
Fuel Cell Using Pentane	$50,000	$65,000	$1100/yr	$4300/yr	$1700/yr	$140,900	$255,900

(1) Development costs to U.S. Air Force are estimated at $2,000,000 if the U.S. Army development program is successful, but are not included in this LCC summary (see Section 2.2.11.1).

(2) See Section 2.2.5 and 2.2.11.2 for description of system being costed

(3) Includes new site preparation, shipment of system to the site, installation and check-out at site

(4) Based on current prices

(5) Life cycle cost of power system per site, excluding cost of development program (see Section 1.5 for description of LCC equation)

current quotes as the instability of prices for petroleum products makes forecasts in this area marginally useful. The out-year fuel costs (and other ownership costs) should therefore be considered as current year dollars.

Also, note that the decision to develop fuel cell power plants for the SEEK FROST program will result in a projected development cost of approximately $2,000,000 to the U.S. Air Force. This cost is based on the assumption that the U.S. Army development program is successful. As the life cycle costs are estimated on a per-site basis, this development cost is not added to the per-site prime power cost in the column headed 'Per-Site LCC,' but must be considered in the overall system cost. Should the U.S. Army involvement be terminated, the development cost to the U.S. Air Force can be expected to be significantly larger.

2.2.13 Outlook

Due to the relatively high electrical energy efficiency projected for the fuel cell power plant and the associated low costs of fuel and fuel transportation, the fuel cell appears to be an economical prime power source. If the system can be designed to meet the goals established for performance and acquisition cost within the schedule established by the U.S. Army, it would be worthy of serious consideration by the U.S. Air Force for application to the SEEK FROST program.

As mentioned previously, the U.S. Army involvement will have a significant impact on the cost to the U.S. Air Force for development of fuel cells. In addition, the procurement cost of the fuel cell power plant will be drastically reduced for the U.S. Air Force should the U.S. Army procurement plan be carried out as scheduled. Hence, the success of the U.S. Army development program must be considered a key factor in the desirability of the fuel cell power plant for the SEEK FROST Program.

2.2.14 Summary for Fuel Cell Power Plant

The development of a fuel cell power plant to meet the requirements of the SEEK FROST program would result in a cost effective unattended prime power source. The key features of the system include:

- High electrical energy efficiency
- Fuel versatility
- Long maintenance cycle with minimal maintenance requirements
- Low operating costs
- Projected reliability is high

It is important to remember that much of the work in the development of fuel cells lies ahead, and that performance

characteristics (i.e. reliability, maintainability, etc.) are in some cases projections at this point. Sufficient test data has not yet been collected to substantiate some of the claims being made. At present, consideration should be given to the following issues when evaluating fuel cell power plants:

- Projected performance characterisitcs have not been verified
- No demonstrated operation in the Arctic environment
- Risk/uncertainty associated with development schedule and cost
- Dependence of development and acquisition cost for the U.S. Air Force on U.S. Army involvement
- Risk associated with production schedule being consistent with SEEK FROST deployment schedule

2.3 DIESEL POWER SYSTEM

The potential use of a diesel engine-generator set as a prime power source for the SEEK FROST Program has been discussed in detail in the GE Unattended Power System Study.(1) This section is not intended to reproduce the detailed analysis provided in the GE Study, but rather to examine those areas which are significantly affected by the change in UAR station load from 2 KW to 5 KW and to provide current information on diesel power systems operating in an unattended mode. Any duplication of information in the GE Study is for completeness. For further detail concerning diesel power systems, the referenced report should be consulted.

2.3.1 Description

The system proposed for the SEEK FROST application is an air-cooled Lister Diesel engine which is direct-drive coupled to a Lima AC generator. The Lister Diesels are considered to be suited for this application as they are designed specifically for remote unattended operation and require little maintenance. The Lister Diesels are currently in use as primary power supplies for lighthouses and other navigational aids in both the U.S. and Canadian Coast Guards.

The Lima AC generator is a self-regulated, brushless, synchronous alternator that has been recommended in the GE Study and is being used by the U.S. Coast Guard. Similar units may be considered applicable, such as a Stamford 'C' range alternator which is used for the Canadian Coast Guard application.

A supplemental power source to provide uninterrupted power during periods which the diesel generator is not on line is also required. The supplemental power would be required during periods which the primary diesel unit has failed and the backup unit is

being started, warmed up, and brought on line. The GE Study suggests a nickel cadmium battery with charger and inverter for energy storage and supplemental power.

2.3.2 Configuration

To satisfy the prime power requirements of 5 KW for a UAR station while unattended and 10 KW when maintenance teams are on site, it is recommended that the diesel power system consist of three Lister ST2A diesel engines coupled to Lima SER-R generators (or a generator of equal capability), with a nickel cadmium battery bank to insure uninterrupted power during diesel engine malfunction. This configuration allows one unit, the primary unit, to be used to supply the 5 KW unattended station load, a second 5 KW generator to be brought on line during maintenance visits, and a third 5 KW unit to insure reliability goals will be met. Further discussion of the rationale for this configuration is presented in Section 2.3.8.

In addition to the power generation equipment above, the design of the diesel power system would include a control system consisting of several control modules, an environmental control system, a fuel transfer system, and an optional fire suppression system.

The 5 KW continuous station load can be supplied by a single ST2A diesel generator set operating at 1800 RPM. Excess power generated may be used to run the control system, battery charger, and environmental control unit. The other two redundant units remain on cold standby to be brought on line in the case the primary unit malfunctions. Alternatively, each of the three systems may be brought on line as the primary unit after some fixed interval of time, thereby dividing the total operating hours equally among the three units. The effects of these two modes of operation on reliability and maintenance requirements would have to be considered before a decision is made on which is preferred. This issue is discussed further in Section 2.3.8.1.

2.3.3 Operation

This section will provide further detail on the function of the various auxilliary support equipment and an overview of the operating sequence for the triple diesel generator system. The system under consideration is based on a design used by the Canadian Coast Guard for diesel power systems at unattended lightstations[2], and appears to be a feasible design for the requirements of the SEEK FROST UAR station.

2.3.3.1 Control System. The control system is divided into modular sub-systems, each of which has a distinct function. These sub-systems are: (1) the engine control module, which, upon receiving an input signal from the logic circuit, controls start/stop sequencing, (2) the generator/environmental control module, which continuously monitors alternator output voltage to ensure operational parameters are met and provides for engine system shutdown if the voltage is not within limits (this module also contains electrical controls associated with the engine room environmental system, to be discussed later), (3) the ballast load module, which automatically adds a ballast load to the alternator when the site load falls below a specified level, thus avoiding prolonged engine running on a light load, (4) the load module, which is responsible for load switching and control to eliminate accidental synchronization of the three power sources, and (5) the logic module, whose function is to determine the availability and functional status of the generator systems under its control. This system may be programmed to alternate the power units at some fixed time interval, or to allow one engine to run continuously with the remaining two engines on stand-by.

2.3.3.2 Environmental Control System. Inadequate engine room ventilation systems can be a major problem area in overall power system performance. For extended periods of unattended operation (six months), the success of the ventilation system will depend upon its filtering capability and its ability to control temperature.

The final design of the environmental control system for the Canadian Coast Guard application consisted of three sub-systems: (1) the air intake and recirculating system, responsible for the intake, mixing, and filtering of air to be used in combustion, (2) the air exhaust and recirculating system, a collection apparatus for the waste heat generated by the engine which is selectively exhausted to the atmosphere or redirected back into the engine room depending on room temperature, and (3) a room excess pressure damper used to eliminate the possibility of over pressurizing the engine room shelter.

2.3.3.3 Fuel Transfer System. The bulk of the diesel fuel required for running the diesel power system may be stored in external storage tanks. A motor driven fuel transfer pump is then used to transfer fuel to a smaller day tank storage facility. This intermediate tank allows for continued fuel supply for a specified amount of time should a failure occur in the transfer system. Thus, the size of the day tank would be determined to allow sufficient time for

maintenance personnel to reach the site, thus preventing the station from going down due to a failure in the transfer system. To eliminate the need for further mechanical fuel transfer, the day tank should be located high enough to permit gravity flow to the diesel engine fuel pump.

The Canadian Coast Guard design utilizes three stages of filtration: between the outside storage tank and the intermediate day tank, between the day tank and the diesel engine, and a final filtering by the engine mounted fuel filter.

2.3.3.4 Fire Suppression System. Should it be deemed necessary, this system may also be included in the diesel power system. The Canadian Coast Guard design includes such a system. Room temperature detectors are used to trigger a gas release valve. The diesel engine which is currently operating is automatically shut down and the stand-by units are prevented from starting. In addition, the ventilation dampers are closed to prevent air from entering the engine room shelter.

2.3.4 Fuel

Use of a diesel power system will not allow the flexibility in the choice of fuel as in the other systems considered. Currently, a special grade of diesel fuel for Arctic applications is being used on the DEW Line, referred to as diesel fuel Arctic. This fuel has a freeze point of -65°F and has proven compatible with the Arctic environment.

2.3.5 Reliability

A detailed analysis of the reliability of a diesel power system is presented in the GE Unattended Power Systems Study.(1) Due to the commonality of parts between the Lister ST2A diesel and the Lister models considered in the GE Study, the failure rate for the ST2A unit may be considered essentially the same as those presented in the report.

The GE Study concludes that the diesel power system will satisfy reliability requirements for a mission time of 2190 hours in an unattended mode. In addition, the report indicates that a six-month interval between maintenance visits may be feasible with further development. The two major areas to be dealt with in attempting to enhance the reliability of the diesel system are failure due to lube oil degradation and injector fouling.

As will be seen in Section 2.3.8, a period of six months operation in an unattended mode has been achieved by the Canadian Coast Guard, and should, therefore, be considered attainable for the SEEK FROST application.

The configuration described in Section 2.3.2 has been suggested for the purpose of enhancing overall system reliability, as failure modes at the engine level are historically of an abrupt and catastrophic nature. Hence, the redundant units are needed to avoid failures at the system level. However, it should be noted that startup failures are not uncommon with diesel engines, and the possibility of such failures should be given consideration when assessing reliability.

2.3.6 Arctic Compatibility

Assuming the presence of an environmental control system as described in Section 2.3.3.2 which will monitor and regulate the temperature of the engine shelter, no problems with operation in the Arctic are foreseen.

At present, diesel power systems ranging in output from 60 KW to 500 KW are used to power sites on the DEW Line. In addition, diesel generator systems are being used to power microwave relay stations for telecommunications in Alaska and light towers at Prudoe Bay, Alaska. Aside from some minor considerations concerning fuel storage and transfer that are common to all candidate systems under consideration, Arctic operation does not appear to present any new or advanced design requirements. Hence, the diesel power systems may be considered compatible with the Arctic environment and no development program for Arctic deployment is foreseen.

2.3.7 Maintenance

Without question, the maintenance required to keep the diesel power system operational is one of the main drawbacks for an unattended application. In addition, the necessity of performing engine overhaul after approximately two and one-half years of operation will add a considerable burden to the logistics task associated with the diesel system.

A maintenance plan is outlined in the GE Study for Lister diesel engine models ST1A and ST3A. As mentioned previously, these models are essentially identical to the ST2A with respect to parts (the basic difference is the number of cylinders). Hence, this maintenance plan is assumed to apply for a model ST2A also.

A more detailed maintenance plan for unattended diesel power systems was provided by the Canadian Coast Guard Marine Aids Division. The maintenance plan applies to the Lister SR3A diesel engine which supplies 8.5 KW of prime power for unattended lightstations. (Note: the Lister SR series has been replaced by the ST series.) The basic maintenance routine is outlined below:

(1) Every three months: inspection check on the primary operating unit; exercising and checking performance of the standby units; inspection of fuel transfer pumps and ventilation system. Time required per visit: 3 hours.

(2) Every six months: perform three-month checks; change lube oil (on primary operating units), injectors, and engine fuel filter; clean and lubricate generator; lubricate ventilation system. Time required per visit: 14 hours.

(3) Every one year: perform three and six-month maintenance routines; inspect bearing, piston rings, and cylinder bores for wear; change cylinder heads; replace all gaskets, lube oil, lube and fuel oil filters. Time required per visit: 27 hours.

(4) Every two years: Base overhaul of primary operating unit. Time required per visit: 48 hours.

Note: Times per visit do not include travel to and from the lightstations.

Personnel from the Marine Aids Division have indicated that the original maintenance schedule included inspection checks at approximately two-month intervals. However, after the first year of operation, it became apparent that a more relaxed schedule would be adequate. Hence, the two-month inspections were discontinued and the maintenance schedule was revised as given above.

2.3.8 Operational Experience

The GE Unattended Power System Study[1] contains information concerning the experience of the U.S. Coast Guard with Lister diesel engines operating in an unattended mode to supply prime power to lightstations and large navigational buoys. The reader is referred to this report for this information. The information contained in this section is based on the experience of the Canadian Coast Guard, which uses Lister diesel engines to power unattended lightstations, and on conversations with Lister representatives.

2.3.8.1 Canadian Coast Guard Experience. A national review of lightstation equipment was initiated by the Canadian Aids to Navigation Headquarters in 1967 with the purpose of determining areas requiring the greatest improvement with regard to operation, reliability and maintainability. Two needs were identified early in the study: (1) determination of the type of power system best suited to the requirements of the lightstations, and (2) uniformity of equipment types and sizes across the country.

Several candidate systems were given consideration, including nuclear power, wind-powered generators, chemical fuel cells, steam engines, gas turbines, batteries, Stirling engines, and diesel engines. Using the criteria of reliability, availability, and cost, diesel generator systems were selected and test and evaluation was begun on commercially available equipment.

Several design criteria were established to make the diesel generator systems suitable for operation in an unattended mode. Some of the crucial requirements decided upon included: (1) system and component standardization, (2) ease of maintenance, (3) maximum reliability, (4) self-monitoring capability, to include automatic shut-down on failure, startup and load change over to a standby unit, (5) unattended operation for periods up to six months, and (6) remote monitoring of the functional status of the system.

Based on the results of a probable peak load analysis, a power requirement of 8.5 KW was determined suitable. Of the 232 lightstations requiring power supply systems, it was determined that 92 stations would utilize diesel generators as their prime power source. It was decided to use commercial land line or submarine cable carrying commercial power as the prime power source for the remainder of the stations, in each case using diesel generators (one or two depending on the reliability assessment of the commercial power) for standby power. This resulted in a requirement for 472 diesel generator systems. Given the 8.5 KW load requirement, the Lister SR3A diesel engine with a Stamford 'C' range brushless alternator was selected, along with associated auxiliary support equipment (see Section 2.3.3 for a discussion of this equipment). The diesel engine utilizes a thirty gallon capacity lubricating oil reservoir tank, providing the engine with a 6000 hour operating capability. All necessary equipment was purchased between 1972 and 1974.

For the 92 stations utilizing diesel generator systems as their prime power source, the triple configuration discussed in Sections 2.3.2 and 2.3.3 was designed. The goal was to provide a system capable of supplying power for a six-month period while operating

in an unattended mode in all conditions found in a maritime environment. Reliability objectives allowed for one diesel engine system failure during the six-month period, as the failure of the operating unit and assumption of the duty cycle by a standby unit would not necessitate a maintenance visit since adequate backup was still available (it is assumed that failure of two diesel engines would require a maintenance visit as backup power would no longer be available). Personnel from the Marine Aids Division of Transport Canada have indicated that this reliability goal has been achieved to date.

The determination of a six-month (4500 hours) unattended operational period was strongly influenced by the fuel injection system employed by the diesel engine. Marine Aids Division personnel involved with testing of the engines and examination of field data indicated that the results showed deterioration of injector nozzles, with subsequent loss of horsepower, when operational hours exceeded 4500 hours. However, with the triple configuration, they felt that a safe figure for total system MTBF would be approximately nine months in an unattended mode.

Section 2.3.3.1 described the operation of the logic control module, wherein it was noted that the system could be programmed to alternate the primary operating unit at some interval of time, or to allow a single engine to continuously operate. In order to determine the effects of these two approaches on total system reliability and maintainability, the Marine Aids Division conducted an eighteen month evaluation of long term single duty diesel operation. The results of this evaluation are of interest should the diesel power system be chosen for the SEEK FROST Program.

The object of the study was to investigate two basic areas: (1) the effects of continuous running of a diesel engine in an unattended mode, and (2) the diesel engine starting reliability after extended periods of inactivity.

Based on the tests that were conducted, the Marine Aids Division concluded that the reliability and performance of the diesel power system are 'greatly enhanced' using a continuous one engine operation. This conclusion was based in part on the following considerations: After initial startup, the diesel engine operates at a fairly constant temperature, virtually eliminating oil leaks due to thermal expansion or contraction. In an automatic system, the 'critical periods' occur during starting cycles involving control sequences, starter motors, lubrication build up, and speed governing. Hence, by eliminating the change over sequence at some fixed time interval (e.g. weekly), the adverse effect of starting

cycles on system reliability is also eliminated. Thus, for the six month (4500 hour) operating period under consideration, it was felt that system reliability would be enhanced by a single engine continuously operating rather than alternating the power units at some predetermined interval of time.

It was also determined during this phase of testing that extended running of up to 4500 hours was achievable without maintenance actions. Hence, this phase of testing demonstrated not only the enhancement to reliability as discussed above, but also the feasibility of a six month maintenance interval for unattended operation.

The second phase of testing was aimed at investigating the other aspect of a continuous one engine operation; namely, the starting reliability of the standby units as a function of the length of the inactive period. Two lengths of inactivity were chosen, two months and twelve months. The conclusions and recommendations follow.

For a two month lay up period, no real problems were experienced, and only a minor adjustment was required as a precaution against delayed lubrication oil pressure build up.

The object of the test with a twelve month inactive period was to 'determine the capability of the prime mover to maintain sufficient internal lubrication after a one year lay up and still be available for emergency start.' Based on the favorable results of the 'two month' inactive tests, the only precaution taken for this test was to seal the air intake and exhaust manifolds by fitting membranes in the air inlet and exhaust ports to prohibit atmospheric breathing.

After one year of inactivity, the interior metallic surfaces of the engine were examined prior to starting the unit. This inspection indicated that adequate oil film was present, from which it was concluded that a standby duty cycle of up to one year is within the capability of the diesel system.

Although the results of the tests discussed above were favorable, a lack of additional data prevented recommendations consistent with the hypotheses being tested. Therefore, the Marine Aids Division recommended the following: (1) the prime power systems convert to a 'one engine' duty cycle, (2) periodic maintenance visits on a ninety day cycle, and (3) exercise of the standby units during maintenance visits, with load transferred to each unit under test for a fifteen minute period. These operating procedures are monitored and may be subject to change as additional operating data is obtained.

Section 2.3.7 presents the maintenance schedule used by the Canadian Coast Guard on a triple engine system. Marine Aids Division personnel have indicated that this maintenance schedule has resulted in excellent overall system performance in that corrective repairs and spare parts required have both been at low levels. On the average, the two year maintenance schedule has necessitated thirty hours for corrective repairs of random failures (excluding travel time) and approximately $1900 for spares cost at a single lightstation.

The maintenance on the equipment is performed by technicians who are 'well versed' in both mechanical and electrical maintenance. Given an individual who is a qualified mechanic, the time and cost required to train this person to the appropriate level of expertise is not excessive. Marine Aids Division personnel estimate a cost of $1000 and at most four weeks to provide all the training necessary to do first line maintenance and trouble shooting on the diesel power systems.

The maintenance actions required for the diesel generator systems are closely monitored through a national 'Fault Reporting System,' whose function is to identify problem areas associated with the power generation equipment. Equipment failures are examined to identify the cause as: (1) component failure, (2) faulty design, or (3) poor maintenance. Based on these failure reports, corrective actions and/or design changes are performed.

Design changes carried out to date on the diesel systems which were initially identified by the Fault Reporting System include: (1) replacement of lubrication oil suction hoses, as the original hoses were suspect when subjected to vibration, (2) replaced engine manufacturer's fuel rack solenoid linkage bushing, (3) converted system operation from alternate engine duty cycle (seven days) to single engine, six month duty cycle, (4) dummy load bank is to be moved inside the diesel room from its present external location, and will interface with the ventilation system to supply heat to the diesel room.

It is these types of changes, which are based on actual field operating experience, that should be investigated if the diesel power system is selected for the SEEK FROST application. By taking advantage of the experience gained by previous users of unattended diesel generator systems, such as the Canadian Coast Guard, many unforeseen problems can be avoided.

The Marine Aids Division has reported that the performance of the diesel power systems has been 'most encouraging', and that their performance objectives have been met. The success of the program has been credited to: (1) careful assessment of equipment needs, (2) prototype evaluation, (3) shop testing and burn-in of all equipment prior to delivery, and (4) training courses for maintenance technicians. Should diesel power systems be deemed suitable for the SEEK FROST Program, similar actions to those above would undoubtedly prove helpful in meeting performance goals.

2.3.8.2 Lister Diesel Representatives. Conversations were held with personnel involved with the marketing of Lister diesel engines who had experience in the operation and maintenance of diesel generator systems. Their views are summarized in the paragraphs below.

For unattended applications of diesel generator systems, Lister representatives indicate that a dry sump lubricating oil system, at least thirty gallon capacity, would be required. This system is the type currently in use by the U.S. and Canadian Coast Guards. This system allows for improved oil cooling and filtration.

It was the opinion of the Lister personnel that the lubricating oil was in fact the limiting factor in extended periods of unattended operation. Should it be desired to extend the maintenance interval beyond six months, a larger dry sump tank would be required along with an improved filtering system. Determination of the size of tank required and design of the filter would be made during a test program.

Another area of concern for unattended operation is lube oil consumption. Lister personnel recommend running a new or overhauled engine for a 250 hour break-in period using a nondetergent lube oil. After this, standard lube oil is used for field operation. Lister users have reported that this process has led to virtually negligible lube oil consumption.

The triple configuration suggested for the SEEK FROST application was discussed, with emphasis on the expected lifetime of the diesel engines given the need for periodic overhaul. Lister personnel noted that although the standard overhaul interval is 20,000 hours for a continuously running engine, actual experience has shown that 15,000 hours gives a longer life for the engine. The suggestion was made to rotate the primary operating unit after three or four overhauls so that all three units would share the twenty year operating life. This mode of operation, they felt, would eliminate the need of replacing the primary unit with a new unit at some point during the twenty year operating lifetime of the system.

Problems inherent with diesel engines were also discussed. The Lister representatives felt that the major cause of engine breakdowns was due to fuel oil leaking into the lubrication oil, causing the dry sump tank to overflow and eventually causing the engine to stop. This is consistent with the information contained in the GE Study concerning the experience of the U.S. Coast Guard with diesel generator systems. Aside from this, no other inherent weaknesses with the system were identified.

2.3.9 Fuel Consumption

Computations presented in this section are based on consumption rates supplied by Lister Diesel representatives for the Lister Model ST2A diesel engine. It is assumed that the fuel for the diesel power system will be that which is currently in use on the DEW Line, diesel fuel Arctic.

To supply the 5 KW UAR station load, Lister representatives recommend running the ST2A diesel engine at 1800 RPM. At this speed and load, the diesel fuel consumption rate is estimated to be approximately 4.5 pounds per hour, or equivalently, .65 gallons per hour.

This rate of consumption is assumed to be realized for 8400 hours per year, giving a requirement of (8400 hr/yr) x (4.5 lb/hr) = 37,800 pounds per year during unattended operation.

During the 360 hours per year that maintenance personnel are assumed to be on site, a standby diesel generator unit will be started to supply an additional 5 KW to meet the 10 KW station load requirement. Thus, during this period, two diesel generator units will be on-line, each using 4.5 pounds of fuel per hour. This results in an additional requirement of 2 x (360 hr/yr) x (4.5 lb/hr) = 3240 pounds per year during maintenance visits.

The total annual fuel consumption is then given by 37,800 + 3240 = 41,040 pounds of diesel fuel Arctic. At seven pounds per gallon, this is equivalent to approximately 5865 gallons per year.

This consumption rate will serve as an input to the computation of fuel cost and fuel transportation cost in the LCC Model.

2.3.10 Life Cycle Costs

The LCC Model used for estimating the acquisition and ownership costs of the diesel power system is given in Section 1.5. The inputs to the model and their source/justification are given below for each cost element.

2.3.10.1 Development. The use of diesel power systems as prime power sources capable of three months unattended operation has been demonstrated. This performance would be consistent with the SEEK FROST maintenance philosophy. Based on the favorable experience reported by the Canadian Coast Guard, it appears that six months of unattended operation is feasible should it be desired. In addition, diesel power systems are currently operating as unattended prime power sources in the Arctic environment. Therefore, it does not appear that further development work will be required for the SEEK FROST application.

2.3.10.2 Procurement. Based on the procurement costs of the diesel power systems procured by the Canadian Coast Guard in 1972 - 1974, the Marine Aids Division of the Canadian Coast Guard has supplied an estimate of procurement costs in 1979 dollars. These costs compared favorably with the estimated costs reported in the GE Study[1], so that either may be considered an accurate estimate. Itemized below are the estimated costs of the triple diesel configuration described in Section 2.3.2 supplied by the Marine Aids Division:

Diesel System (see Section 2.3.2):	$39,000
Triple diesel alternator units	
Ventilation System	
Control System	
Diesel Fuel Day Tank	
Dual transfer pumps (fuel)	
Load Bank	
Battery charger and Diesel Battery	
Fire Suppression System	$ 1,700
Prefabricated Diesel Shelter	7,700
Diesel Fuel Storage Tank	3,000*
Total	$51,400

(*Based on cost estimate in GE Study as it was not included in the Marine Aid Division estimate)

The GE Study costed a similar system and estimated the cost of a diesel power system at $54,000 per site. Due to the uncertainty inherent with these types of estimates, the more conservative estimate of $54,000 will be used here.

2.3.10.3 Installation. The installation cost for the diesel system is based on the cost contained in the GE Study(1). As with the other candidate systems, the cost for installation is dominated by the site preparation cost associated with a new site. The installation cost is assumed to average $65,000 per site.

2.3.10.4 Maintenance. The maintenance schedule used by the U.S. Coast Guard is presented in the GE Report. For the purposes of this report, the maintenance schedule presented in Section 2.3.7 will be used as the information supplied by the Marine Aids Division of the Canadian Coast Guard is quite detailed with respect to time and manpower requirements. As the maintenance schedule is based on a two-year (18000 hr) interval between overhauls, the approach taken here is to estimate the cost of maintenance (parts and labor) over the two-year period, and then to convert this to an annual cost.

Time requirements for the maintenance schedule are computed based on the following assumptions: (1) Over the two-year period, the three-month inspection visit is made a total of four times, at the third, ninth, fifteenth, and twenty first months; (2) the six-month maintenance routine is performed twice, at the sixth and eighteenth months; (3) the one-year maintenance action and two-year overhaul routine are performed only once, at the twelfth and twenty-fourth months, respectively. This schedule essentially describes the routine followed by the Canadian Coast Guard.

Using the time requirements per visit given in Section 2.3.7, the total time required for the two-year maintenance interval is given by:

3 Month Inspection Visit:	3 hr/visit x 4 visits	= 12 hours
6 Month Maintenance Routine:	14 hr/visit x 2 visits	= 28 hours
1 Year Maintenance Routine:	27 hr/visit x 1 visit	= 27 hours
2 Year Base Overhaul:	48 hr/visit x 1 visit	= 48 hours
	Total preventive maintenance	=115 hours

Note: These times do not include travel times as it is assumed that dedicated maintenance trips for the prime power system will not be necessary unless emergency corrective action is required. Routine preventive maintenance will be scheduled to coincide with maintenance visits for radar and communication equipment.

In addition to the time required for preventive maintenance, the Marine Aids Division has reported an average of thirty hours required over the two-year interval for corrective repairs of random failures. This gives a total requirement of 145 hours dedicated to diesel system maintenance over the two-year maintenance interval.

Current contractor costs for diesel mechanics capable of maintaining and overhauling the diesel systems on the DEW Line are estimated by personnel in the DEW Systems Office to be twenty dollars per hour. This gives an average cost of labor over the two-year period of $2900.

In addition to the time requirements for maintaining the diesel generator systems in use by the Canadian Coast Guard, the Marine Aids Division also supplied data on the cost of spare parts for the diesel system. Over the two-year maintenance interval, the average cost for spares parts is reported as approximately $1900 for the triple diesel configuration.

Also of interest is the cost of lubricating oil. The Canadian Coast Guard performs two oil changes per year on the primary operating unit, and one oil change per year on the two standby units. Assuming a thirty gallon dry sump oil tank, this maintenance routine would necessitate 120 gallons of lubricating oil annually at each site. Using a cost of $1.00 per quart of lubricating oil, the cost comes to approximately $500 per year.

The final cost to be accounted for is a transportation and installation cost associated with returning the overhauled diesel engine to the site. For the purposes of this report, overhaul at the UAR station's logistic node will be assumed. The cost of transportation and installation is estimated to average $1000 (includes helicopter flight time).

Converting those costs which are based on a two-year maintenance interval to annual costs results in an average annual maintenance cost for the triple diesel configuration of $3400.

2.3.10.5 Fuel (FC). Section 2.1.10.5 reported an average cost of $.78 per gallon for JP-4 jet fuel currently being used on the DEW Line. Personnel from the DEW Systems Office have indicated that the average cost of the diesel fuel Arctic being used for the diesel power systems currently in use on the DEW Line is also $.78 per gallon.

Section 2.3.9 contains the computations concerning fuel consumption rates for the diesel power system. The projected annual rate of consumption is 5865 gallons. This results in an average annual fuel cost of:

$$FC(\text{diesel}) = 5865 \text{ gal/yr} \times \$.78/\text{gal} = \$4575/\text{yr}.$$

2.3.10.6 <u>Fuel Transportation (FT)</u>. The helicopter shuttle operation between the resupply vessel and the UAR site storage tanks that is assumed for this report is described in Section 1.5.2. Section 2.1.10.6 also contains assumptions concerning the costs of this operation. The reader is referred to these sections for a detailed description of the fuel transportation operation and associated costs.

The diesel power system is assumed to require 5865 gallons of diesel fuel Arctic per year, or, at seven pounds per gallon, 41,040 pounds per year. Based on a helicopter capacity of 5000 pounds of fuel per trip, an average of nine round trips will be required from the resupply vessel to the UAR station.

Using the time factors of Section 1.5.2, each round trip from the resupply vessel is assumed to require an average of twenty minutes. Thus, the site refueling operation will require

$$9 \text{ trips} \times 1/3 \text{ hr/trip} = 3 \text{ hours}.$$

At a rate of $1000 per flight hour, the average cost of helicopter flight time is estimated to be $3000 for the refueling of a UAR site.

Using a similar argument to that presented in Section 2.2.11.6 concerning contractor support personnel, the average cost of the four support personnel is assumed to be $320 for each UAR site. This results in an average annual fuel transportation cost of FT = $3320 for diesel fuel Arctic required by the diesel power system.

Summing the cost of diesel fuel Arctic computed in Section 2.3.10.5 and the fuel transportation cost computed above gives the average total annual cost of supplying diesel fuel to the UAR sites: FC + FT = $7895. This results in an average unit cost of diesel fuel Arctic delivered to the UAR site storage facility of $1.35 per gallon, or $.17 per KWH.

The results of the fuel cost and fuel transportation cost computations are summarized in Table 7 below. Table 8 contains the on-site delivered cost of diesel fuel Arctic broken out as purchase, sealift, and helicopter shuttle.

2.3.11 Life Cycle Cost Summary

The life cycle cost associated with the acquisition and ownership of the diesel power system for the SEEK FROST UAR site is shown in Table 9. The out-year fuel costs (and other ownership costs) are based on current costs of fuel and labor. Therefore, these ownership costs should be considered to be reported in current year dollars.

2.3.12 Outlook

The configuration suggested in Section 2.3.2 utilizes Lister ST2A diesel engines. The ST series of Lister diesel engines replaced the SR series, which is used by both the U.S. and Canadian Coast Guards, near the end of 1976. The main improvement in the ST series is increased power with nearly identical fuel consumption to the SR series.

Lister representatives have indicated that minor improvements are always being sought with the diesel engines. Many changes are incorporated within a given series of engine without a change in the actual designation. These changes are usually of a minor nature, and a new series is introduced only when significant improvements in performance are anticipated. As such, the ST series is expected to remain Lister's prime diesel system for the next 10-15 years. Hence, no significant changes are to be expected prior to SEEK FROST deployment.

2.3.13 Summary for Diesel Power Systems

The ability of diesel generator systems to provide prime power while operating in an unattended mode for three month periods has been demonstrated. All necessary equipment is currently available for procurement and such a system would present no new logistics problems. The primary features of the diesel power systems include:

- Relatively low acquisition cost
- Arctic compatibility has been demonstrated
- Preliminary indications show six months of unattended operation is possible

TABLE 7

Annual Fuel and Fuel Transportation Costs for Diesel Fuel Arctic Required for UAR Sites Powered by Diesel Power Systems

	Unit Cost of Fuel[1] (Purchase + Sealift)	Annual Consumption	Fuel Cost (FC)	Helicopter Cost	Support Personnel Cost for Shuttle	Total Shuttle Cost (FT)	Delivered[3] Cost of Fuel
Diesel Fuel Arctic	$.78/gal	5865 gal[2]	$4575	$3000	$320	$3320	$.17/KWH

(1) See Section 1.5.1 for discussion of unit cost of fuel

(2) 7.00 pounds per gallon

(3) Load of 5 KW for 8400 hr/yr = 42,000 KWH
Load of 10 KW for 360 hr/yr = 3,600 KWH
Total annual energy requirement = 45,600 KWH

TABLE 8

Per Cent of On-Site Delivered Cost of Fuel Attributed

to Purchase, Sealift, and Helicopter Shuttle

For Diesel Power System

	% Due to Purchase	% Due to Sealift	% Due to Helicopter Shuttle
Diesel Fuel Arctic	37% ($.50/gal)	21% ($.28/gal)	42% ($.57/gal)

TABLE 9

Life Cycle Cost Summary for Diesel Power System at a UAR Site(1)

(FY79 Dollars Rounded to Nearest $100)

	Acquisition		O&M				
	Procurement(2)	Installation(3)	Maintenance (Parts + Labor)	Fuel(4)	Fuel Transportation	20-year O&M(5)	Per-site LCC(5)
Triple Diesel Power System	$54,000	$65,000	$3400/yr	$4600/yr	$3300/yr	$225,900	$344,900

(1) It is assumed that no development program will be required for this system

(2) See Section 2.3.2 and 2.3.10.2 for description of configuration being costed

(3) Includes new site preparation, shipment of system to the site, installation and check-out on site

(4) Based on current prices

(5) See Section 1.5 for description of LCC equation

The drawbacks associated with the diesel power system include:

- Failure mode at engine level is usually abrupt and catastrophic
- Amount of time required during maintenance visits may be large
- Possibility of startup failures may adversely affect overall system reliability
- Need for skilled maintenance technicians to maintain diesel engines
- Periodic overhaul (two year) presents additional logistics tasks

SECTION 3

OTHER ISSUES

During the course of this study of the three candidate power systems discussed in Section 2.0, questions have been raised which are related to the area of unattended prime power and are worthy of some discussion. This section is intended to provide a brief presentation of some of the issues and, where applicable, to provide any conclusions that may have been reached.

3.1 LIMITS ON UNATTENDED POWER SOURCES

The analysis performed for this report is based on UAR station load requirements of 5 KW while the site is unattended and 10 KW during periods which maintenance personnel are on site. These requirements were formulated on the assumption that an unattended radar and communication system could be developed such that the entire station load would not exceed 5 KW (including weather sensors, navigational aids, alarms, etc.)

Due to the time and expense involved with such a development program, the possibility exists that the SEEK FROST program may resort to procurement of a currently available 'unattended' radar to satisfy the gapfilling requirement. Obviously, the definition of unattended is ambiguous and has a specific but unspecified time dimension. As such, consideration must be given to the capability of an unattended prime power generation and distribution system to provide significantly higher levels of power for a period of time consistent with the SEEK FROST UAR station maintenance concept. Power requirements for a UAR station in the range of 60-70 KW should be expected should this option be taken.

For each of the power systems considered in this report, some insight was gained as to what might be considered a feasible upper bound for unattended prime power generation for the SEEK FROST application. The following paragraphs summarize what was learned for each type of system.

R&D personnel at Ormat Turbines Ltd. indicated that a 60 KW Ormat Energy Converter is currently under development and is scheduled for production in the fall of 1981. The system is projected to achieve an electrical energy efficiency of approximately 22% and will consume close to 6.7 gallons of jet fuel per hour. The suggested configuration is two such units, each supplying one-half of the station load, thereby providing hot standby redundancy. The projected sale price for the 60 KW unit is between $80,000 and $100,000, depending on adjustments for fluctuating price levels and quantity buys.

The development of fuel cell power plants capable of meeting station load requirements in the 60-70 KW range appears to be further along than the programs discussed in Section 2.2.3, which are concerned with much smaller systems. United Technologies Corporation (UTC) has developed a 40 KW fuel cell designed to operate unattended. The unit runs on natural gas, but can be modified to operate on most any hydrocarbon fuel. The 40 KW unit achieves an electrical efficiency of 40%. UTC personnel suggested a configuration of three such units, two units sharing the station load and one unit on cold standby. As a significant demand for this unit has not yet materialized, only one unit has been built and an estimate of the sale price was not determined.

The Energy Research Corporation (ERC) is also developing large fuel cells in the range of interest. Currently being developed by ERC is a 60 KW unit which is to be used to supply prime power and heat for shopping centers. The units are to achieve an electrical efficiency of 40% and are being designed for unattended operation for a period of one year. A configuration of two such units was suggested, each supplying one half of the station load. Should one unit fail, the other unit is capable of operating in an overload condition for an extended period of time. Hence, meeting the reliability requirements was not considered a problem by ERC personnel, even if the station load were as high as 75-80 KW.

The third candidate system, the diesel engine generator set, appears to be the least desirable for the higher load requirement. Personnel from the DEW Systems Office indicated that diesel systems currently in use on the DEW Line (ranging in size from 60-500 KW output) are usually visited three times daily for inspection, adjustment, or repair. They felt that if the diesel power systems were to be used in an unattended mode, the UAR station load would have to be kept under 10 KW. Above this level, the diesel units would require frequent attention, to the point that it would not be consistent with the SEEK FROST maintenance philosophy.

3.2 ISOTOPE FUELS FOR UNATTENDED POWER SYSTEMS

The GE Unattended Power Systems Study[(1)] provides detailed analysis for the organic Rankine cycle (the principle on which the Ormat Energy Converter operates) and Stirling power conversion systems operating on nuclear isotopes. The conclusions reached in this study included: (1) the cost associated with an isotope fueled system are dominated by the isotope heat source assembly and shield costs, (2) the risk in development of isotope fueled systems would be at an acceptable level in light of performance characteristics

and cost reductions to be realized, (3) the isotope fueled systems have the potential of reliably providing power without dependence on diminishing (and increasingly expensive) fuel supplies, and (4) isotope fueled systems are generally not cost competitive unless the isotope fuel (Strontium 90) is supplied free of charge. In addition to these conclusions, it is clear that the desirability of an isotope fueled system would depend on a favorable environmental impact statement.

Of the above conclusions, the fourth is quite important as it has a significant effect on the desirability of isotope fueled systems. At the time the GE Study was performed, the cost of Strontium 90 was $.10 per curie plus shipping. A Department of Energy (DOE) source has indicated that the cost of Strontium 90 has not changed, and that the analysis and conclusions concerning isotope fuels that are presented in the GE Study should still be considered accurate. The reader may reference this report for detailed cost analysis concerning isotope fueled systems and the effect of the price of Strontium 90 on life cycle cost.

Should there be a change in the status of the DOE policy concerning the cost of Strontium 90 for military applications, only one of the candidate systems considered in this report would be affected, namely the Ormat Energy Converter which utilizes the organic Rankine cycle concept of operation. Ormat Turbines Ltd., in collaboration with the French Atomic Energy Commission, has developed a radioisotopic heated unit. This power generator consists of a compound system which utilizes two fluid cycles, the interaction being at a heat exchanger which serves as a condenser for the primary cycle and a boiler for the secondary cycle.

The radioisotopic heat source is based on the decay of Cobalt 60. In spite of the continual decay of the radioisotope, special controls were developed to maintain a constant DC output voltage. The overall electrical efficiency of the system at an output of 680 watts is 8.5%. The integrated system was installed in France at a microwave relay station site in March 1971 and has been operated continuously since that time.

Although the power output is considerably less than would be required for the SEEK FROST application, this system has proved the feasibility of such a power conversion system. For a larger system, such as a 5 KW unit applicable to the SEEK FROST Program, the concept of operation would be unchanged so that the time and cost for development would be kept minimal. The desirability of such a system is largely dependent on the cost and availability of alternative fuels on which the OEC can be operated, as the use of isotope fuels would introduce added restrictions in handling.

3.3 WIND ENERGY CONVERSION SYSTEMS

The GE Unattended Power Systems Study(1) examined a candidate system consisting of a Vertical Axis Wind Turbine (VAWT), energy storage batteries, and diesel engine generator sets. When wind is available at sufficient speed to run the VAWT, this system supplies the station load, with excess power used to charge the storage batteries. In the absence of sufficient wind, the necessary power is drawn from the storage battery until it is discharged. At this point, the backup diesel power system is activated to supply power for the station and charge the battery until sufficient wind is available.

The primary disadvantages of this system include: (1) wind availability data would be required for potential site locations, (2) current data suggests that a wind-powered system may not be compatible with all unattended sites, (3) the possibility of long periods of calm would require large storage batteries, which may prove costly, and (4) inherent startup problems with diesel engines could result in unacceptable station downtime.

The first item above is vital to an accurate assessment of the cost-effectiveness of a wind-powered system. An extensive wind survey would be required at each potential UAR site to determine, as a minimum, reasonably accurate estimates of two key factors: (1) the percent of time which sufficient wind is available to run the VAWT, and (2) the frequency of occurrence of extended periods of calm which would necessitate startup of the diesel power system.

Both of these factors will influence the desirability of a wind-powered system. The first will aid in determining the compatibility of a potential site and a wind-powered system. Obviously, if sufficient wind is not available a large portion of time, the amount of 'free' energy from the VAWT may not offset the investment cost for the system. Similarly, if sufficient wind is available much of the time, the wind-powered system essentially becomes a free energy source, making the investment more desirable.

The second factor is also important in the analysis of the cost-effectiveness of the system, and will also play a significant role in assessing the reliability of the system. During extended periods of calm which require the diesel system to be activated, the electrical energy that is provided is more costly, as the operating costs associated with the diesel system are higher than those of the VAWT or the storage batteries. In addition, maintenance costs associated with the diesel system will rise with the increased amount of operating hours. Hence, the more time the diesel system is required, the higher operation and maintenance costs can be expected to climb.

From a reliability viewpoint, the need to bring the diesel system on-line will, in general, have an adverse effect on overall system reliability due to the possibility of a startup failure. Note that the diesel power system is required when sufficient wind is not available to drive the VAWT and the storage battery has been discharged. At this point, the UAR station is dependent on the ability of the diesel power system to successfully startup and supply the station load. The more often this situation is encountered, the less desirable the overall system becomes in terms of reliability. In addition, having a reasonably accurate estimate of the number of times the diesel system will be required and the probability of a startup failure will allow an estimate of system downtime to be made. This information can then be used to determine whether the projected amount of downtime is compatible with the SEEK FROST requirements, and whether the associated maintenance costs are tolerable.

From these considerations, it is clear that the collection of wind availability data must be done in such a way as to provide an accurate characterization of the conditions at each potential UAR site if a meaningful cost-benefit analysis is to be performed. The feasibility of such an effort, and the time and cost associated with such an activity, must all be given consideration when evaluating the desirability of a wind energy conversion system.

The second disadvantage given above also deserves attention. The GE Study concludes from the wind availability data that was examined that there is a significant chance that not all potential UAR sites would be compatible with a wind-powered system. Given this conclusion, and assuming that diesel power systems are not the preferred prime power source for those sites without sufficient wind, a decision to deploy wind energy conversion systems at suitable locations would result in a loss of commonality of power systems on the line. As such, attention would need to be given to the impact on logistics support and maintenance requirements associated with the deployment of two different prime power sources.

The third and fourth items above are interrelated and provide an area for further analysis to enhance system performance and reduce operating costs. Based on the discussion above, it is clear that the effect of frequent and/or prolonged use of the diesel power system is to reduce the reliability of the system as a whole and to drive the operation and maintenance costs upward. By acquiring large battery storage units, the need for the diesel system should be reduced, as only an occasional period of extended calm would cause the batteries to discharge. Thus, a savings may be realized by minimizing the amount of time and number of times which the diesel system is required. This savings would be weighed

against the acquisition cost of the large batteries to identify which option is the more desirable. In either case, it is clear that the dependence on the wind will result in an additional cost for uninterrupted power, the magnitude of which may be considerable.

In general, although the concept of wind as a free energy source appears appealing, the issues raised in this section indicate that there are costs associated with this type of system which are not initially apparent. In addition, the reliability of such a system is largely dependent on the random behavior of the wind, which is at best difficult to characterize. In turn, the problem of optimum siting and design becomes complex, and may involve significant amounts of time and money in R&D work.

The final judgement to be made with respect to wind energy conversion systems will depend on whether a high technology program such as SEEK FROST, whose mission is critical to the air sovereignty of North America, should rely on an energy source which is as inherently unpredictable as the wind.

SECTION 4

SUMMARY AND CONCLUSIONS

This report has considered three prime power generation systems and their ability to satisfy the SEEK FROST UAR station power requirements. Although the life cycle cost associated with the acquisition and ownership of each system has been considered, operational experience with the systems in unattended applications and other characteristics have been evaluated as well. These characteristics include: the development risk associated with the system, the reliability of the system, and the ease with which the system may be kept in an operational mode, i.e. maintainability. All of these areas should be considered in detail before a final decision is made on which system is preferred for the SEEK FROST Program.

The following paragraphs present conclusions that have been drawn concerning the candidate systems, and also raise issues which must be considered when evaluating the desirability of each system for the SEEK FROST Program.

Section 2.1.14 presented a summary of the characteristics for the Ormat Energy Converter. The favorable characteristics are considered self-explanatory and do not require further discussion. The features which adversely effect the desirability of the OEC are given further consideration.

The relatively high acquisition cost of the OEC may be justified when one considers the proven reliability of the OEC units. It is doubtful that any other system will be able to claim such reliable operating experience in an unattended mode in the harsh Arctic environment. Although highly reliable performance in an unattended mode of operation is difficult to quantify in terms of cost savings, its effect on the operating costs of the system (i.e. preventive/corrective maintenance actions and associated transportation costs) should be weighed against the acquisition cost. The SEEK FROST program involves a si ificant technological advance for an unattended radar and communication system. It would seem that the high acquisition cost associated with an extremely reliable prime power source can be justified on the grounds of enhancing UAR station reliability, and in effect eliminating an additional area of concern.

Hence, the issue concerning acquisition cost appears to be determining the value that should be placed on proven high reliability, and a decision must be made as to whether the acquisition cost of the system is a fair price to pay for this reliability. When

comparing this cost with the cost of alternative systems, the effect of reliability on the overall performance of the system and the associated cost of maintaining the system (i.e. time and manpower required, spare parts, transportation, etc.) must be considered. An attempt to realize a savings in acquisition cost at the expense of reliability may prove to be a costly decision over the life of the system.

Concerning the low electrical efficiency of the system and its impact on associated fuel costs, the development programs currently in progress, if successful, will provide significant improvements and make the OEC even more desirable (see Section 2.1.13). This assumes that the reliability of the units will be at least at their present level. Even though the electrical efficiencies being forecast are not as high as some prime power systems, the improvements will provide a system with competitive operating costs, together with other cost-effective features that other systems cannot claim.

Section 2.2.14 presented a summary of the pros and cons associated with the development and procurement of fuel cell power plants. Again, the desirable features need no further explanation. The problems associated with the fuel cell power plant are discussed in further detail below.

The risks associated with the cost and schedule of fuel cell development is a significant drawback of this alternative. The development of an unattended radar and communications system that satisfies the SEEK FROST requirements will have some degree of risk associated with it as to cost, schedule, and performance. Thus, the choice of a fuel cell power plant as an unattended prime power source will present another area of uncertainty in the overall development of the SEEK FROST system, thereby reducing the overall probability of program success. Before a verdict is reached on the fuel cell power plant for the SEEK FROST application, a detailed risk assessment would be necessary, followed by preparation of a risk management plan. In this manner, a determination could be made as to whether the risk involved with fuel cell development is at an acceptable level given the merits of the system presented previously.

Although the fuel cell power plant appears to be a very desirable alternative to the unattended power requirement, the dependence on the U.S. Army involvement makes predictions concerning cost and schedule unreliable at this point. Considering the proposed deployment schedule for the SEEK FROST Program, delays in the development and production schedules for fuel cells could cause problems for the U.S. Air Force application (although this may not be the case

for the U.S. Army program). Therefore, the U.S. Air Force involvement may need to be initiated early in the development program so that the risks in schedule can be identified and hopefully reduced, insuring a production schedule consistent with the needs of the SEEK FROST program.

In summary, if the fuel cell development plan proceeds as scheduled and performance expectations are met, a highly efficient unattended prime power source with low operating costs will be available for deployment in the SEEK FROST system. Due to the uncertainties associated with its development in terms of cost, schedule and performance, a final judgement on its desirability cannot be made at this time.

The diesel power system is summarized in Section 2.3.13. The desirability of diesel generator systems hinges primarily on its comparatively low unit acquisition cost (recall that the fuel cell power plant procurement cost is dependent on the success of the U.S. Army development program and is expected to be significantly higher should the program be terminated). In addition, recent experience with diesel power systems operating as unattended power sources indicates that a six-month maintenance interval may be attainable.

Based on the experience of the U.S. Coast Guard as documented in the GE Study[1], and the experience of the Canadian Coast Guard as reported in this report, the diesel power system appears to be capable of reliable performance in an unattended mode. However, it is important to note that diesel power system reliability is achieved through careful, and somewhat extensive, maintenance procedures requiring time, manpower, and materials. The need for such attention is basically a result of the large quantity of moving parts associated with an internal combustion engine.

In contrast to this, the other candidate systems achieve high levels of reliability by utilizing alternative concepts of operation which minimize the number of moving parts. For example, the Ormat Energy Converter, which operates on an organic Rankine cycle, has only one moving part. Thus, the reliability of other systems is achieved through design, while reliability of the diesel system is achieved by periodic maintenance aimed at retarding wear and degradation of the system's components. As either approach appears to satisfy the SEEK FROST reliability requirements, the preference of diesel power systems will depend on the cost and availability of maintenance personnel required to achieve a given level of reliability. The need for such intervention must be given full consideration in assessing the desirability of diesel power systems for the SEEK FROST application.

From the above discussion, it is clear that a reliable prime power generation and distribution system is currently available; however, the means by which reliability is attained varies. (As reliability associated with the fuel cell power plant is currently a projection, this discussion centers on the two candidate systems which are currently available for deployment.) In the case of the Ormat Energy Converter, reliability is inherent in the design of the system (and therefore maintenance requirements are minimal) and is essentially purchased, and is indicated by the high procurement cost. The diesel system, while much less costly to procure, relies heavily on its maintenance requirements to achieve reliable performance. The preference of one system over the other, in terms of reliability, essentially depends on a choice between two alternative courses of action: (1) expenditure of a large amount of funds in the acquisition phase for an inherently reliable system with minimal maintenance requirements, or, (2) expenditure of a more modest amount of funds initially for a system which will incur greater costs of maintenance during the ownership phase.

It should be noted that the fuel cell power plant, although requiring a development program which involves a fair amount of technical, cost, and schedule risk, appears to offer the advantages of the two systems given above should the projections concerning cost and performance be realized. Specifically, successful development of the fuel cell power plant will result in a prime power system with a moderate procurement cost, minimal maintenance requirements, high electrical efficiency (i.e. low operating costs), and reliable performance. Thus, the progress of the fuel cell development work should be closely monitored as this system is potentially a strong candidate for the SEEK FROST UAR station prime power generation system.

Another area which lends itself to comparison among the candidate systems is the fuel that is utilized, and the cost of such fuels.

The fuel cell power plant is capable of operating on most any type of hydrocarbon fuel. The desirability of such a fuel for use in the fuel cell depends primarily on its cost, the ease with which it is reformed to a hydrogen-rich gas, the BTU content, availability, and whether pre-processing is required. Although JP-4 jet fuel has been considered due to the favorable impact on logistics, many other fuels would need to be evaluated using the above criteria before a final decision is reached.

The diesel power system has the least amount of versatility among the systems considered, and hence the fuel costs are totally dependent on the price of oil. Given the current state of affairs, this price can be expected to increase, perhaps significantly, before the scheduled deployment of the SEEK FROST system. Unless cost competitive alternative sources of oil are found, such as a coal-to-oil conversion process being used in South Africa, dependence on foreign oil prices could prove costly over the life of the diesel system.

Of the three candidate systems considered in this report, the Ormat Energy Converter is unquestionably the most versatile with respect to the types of fuel on which it can operate (see Section 2.1.3). This feature has the effect of eliminating the dependence of fuel costs on foreign oil prices. Thus, a price level can be established for imported oil above which alternative fuels are considered cost effective. For example, OEC units are currently available that utilize methyl alcohol for fuel. Although currently not economically viable, this fuel is not linked in any way to the price of oil and therefore may become more attractive as oil prices continue to spiral. In addition, development of synthetic fuels will provide another alternative to petroleum-based products.

The importance of the OEC fuel versatility is best demonstrated by considering the following: (1) an area of tradeoff is provided as many fuels can be considered to determine which will have the most beneficial effect on operating costs, and (2) the power system can be easily converted to operate on a different fuel type should unforeseen increases occur in the price of the fuel in use.

Considering the current stage of development of fuel cell power plants, no definite conclusion concerning the choice of an unattended power generation system for the SEEK FROST UAR station is presented at this point. However, some points can be made concerning the candidate systems based on the information that is currently available.

Currently, manpower requirements account for a large portion of DEW Line operating costs as the age and design of the system are such that constant maintenance is required. System reliability and availability are good, but again, this performance is a result of constant attention given to the system rather than through redundant design or the use of highly reliable components. As such, the operating personnel spend the majority of their time on corrective, rather than preventive, maintenance tasks. The end result is that operating costs are essentially dependent on the cost of labor, which, in an Arctic environment, is significant.

In addition to enhancing the detection capability of the DEW Line, the SEEK FROST Program is intended to provide a surveillance network that reduces manpower requirements in the Arctic, thereby reducing operating costs. This goal is to be accomplished primarily through the concept of an unattended radar station, which, through redundant design and high reliability components, will be capable of reliable performance for extended time periods.

Consistent with the philosophy of the SEEK FROST Program, it would appear that the UAR station power generation and distribution system should be a highly reliable system which requires minimal maintenance. Given the two systems currently available that are considered in this report, the Ormat Energy Converter appears to be the superior system with respect to these criteria. The operational experience in the Arctic environment has resulted in highly reliable performance. In addition, the design of the system is such that maintenance is minimal and inexpensive.

The life cycle cost associated with the OEC is high when compared to diesel power system cost (and projected costs for the fuel cell power plant). The higher costs are attributed primarily to the cost of procurement, the cost of fuel and the associated transportation cost of the fuel. However, two factors may result in reducing the gap in life cycle costs between the OEC and diesel power systems: (1) the development programs currently in progress at Ormat Turbines Ltd. should result in a more efficient system, thereby reducing fuel and fuel transportation costs (see Section 2.1.13), and (2) based on recent trends, the cost of diesel fuel can be expected to increase, perhaps significantly, by the time of SEEK FROST deployment resulting in increased fuel costs for the diesel power system (the issue of diesel fuel availability throughout the life of the SEEK FROST system should also be given consideration).

Although these are projections, the point should be stressed that due to the impact of the prime power system on UAR station reliability and maintenance costs, life cycle cost should not be used as the only criterion by which candidate systems are evaluated. Hence, if savings in UAR station costs are desired, perhaps areas other than the prime power system should be analyzed for cost tradeoffs, as the power system is crucial to the overall success of the program.

Table 10 below provides a summary of the three candidate systems considered in this report using the criteria which are considered most important in their evaluation. Examination of this table indicates that no one system appears superior in every area, but rather each system has strengths and weaknesses associated with it.

TABLE 10

Summary of Candidate Prime Power Systems

System	Fuel	Reliability	Arctic Compatibility	Maintenance Requirements	Efficiency	Per-Site LCC	Outlook
Ormat Energy Converter	Operates on any heat source	Excellent	Demonstrated	Minimal	Low (11%) (1)	\$449,200/ \$621,300 (3)	Improved efficiency
Fuel Cell Power Plant	Hydrocarbon Fuels	Not yet determined	No problems foreseen	Projected as minimal	Projected as high (28-37%) (2)	\$234,900/ \$255,900 (4)	Risk in development
Diesel Engine Generator	Diesel Fuel Arctic	Good but manpower dependent	Demonstrated	Heavy	Medium (18-20%)	\$344,900	No changes foreseen

(1) Hybrid configuration (see Section 2.1.4)

(2) Dependent on load and type of fuel

(3) Operation on JP-4 Jet Fuel/Propane

(4) Operation on JP-4 Jet Fuel/Pentane

Thus, the final decision on a prime power system will depend on which of these criteria are considered the most crucial to the success of the SEEK FROST Program.

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LIST OF REFERENCES

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2. M.C. Armstrong and C.H. Fawns, Power Supply Systems for Unattended Lightstation Operation, Transport Canada, Marine Aids Division.